User Guidelines for Waste and By-Product Materials in Pavement Construction

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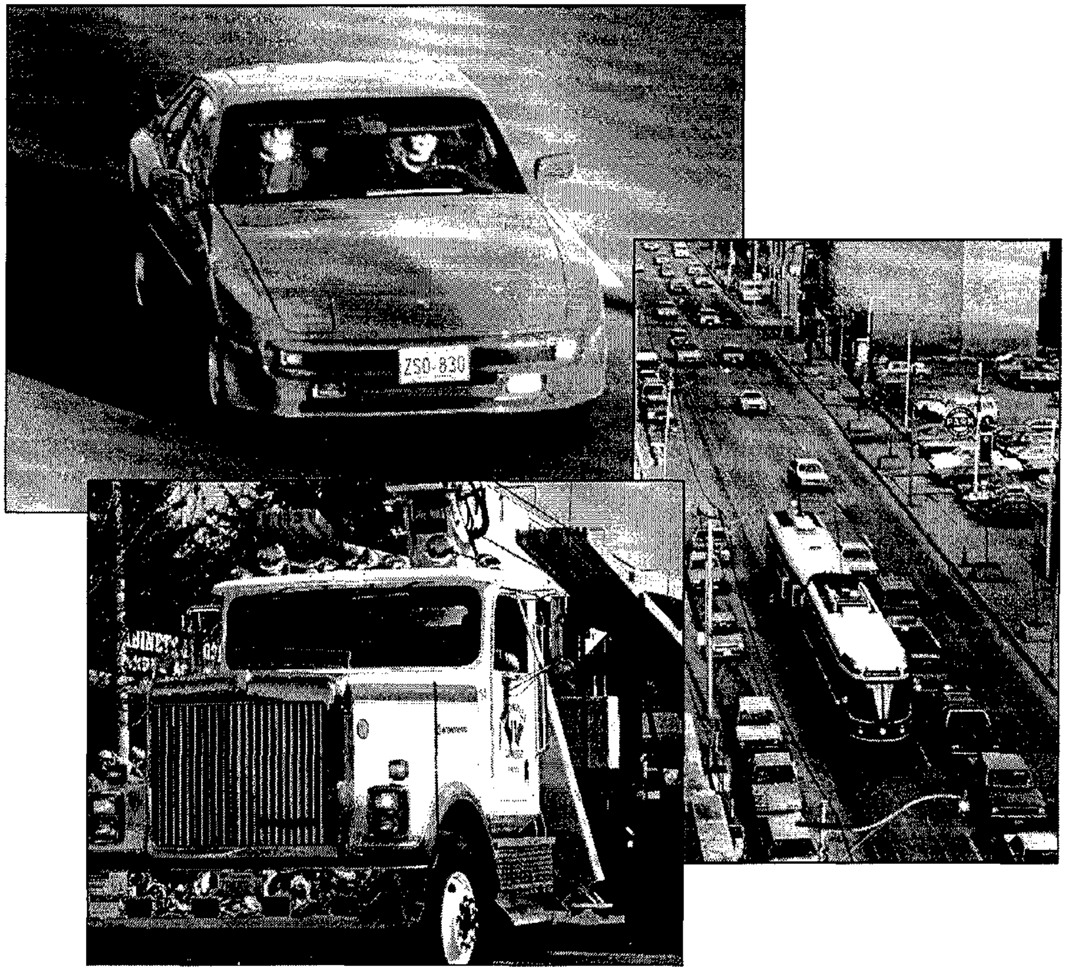

U.S. Department of Transportation
Federal Highway Administration

Research and Development
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

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FOREWORD

This user guideline manual presents the results of research conducted for the Federal Highway Administration (FHWA) on the use of waste and byproduct materials in pavement construction. This document will be of interest to highway engineers and materials engineers, as well as waste and byproduct producers and others involved in decision-making regarding the use of waste and byproduct materials in pavements.

This document is a concise compilation of available information on 19 waste and byproduct materials and guidelines for their use (where appropriate) in 7 pavement construction applications. General information on evaluating the suitability of a waste or byproduct material for use in pavement construction, including engineering evaluation, environmental issues, and cost issues, is also provided.

The looseleaf format of this manual allows for updates and revisions as more information becomes available. The manual will also be available in electronic format on CD-ROM and will be accessible via the Turner Fairbank Highway Research Center (TFHRC) Web site.

Charles J. Nemmers, P.E.
Director, Office of Engineering
Research and Development

NOTICE

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16. Abstract

The objective of this project was to develop a concise, easy-to-use manual containing the latest available information on the use of waste or by-product materials in pavement construction applications. The manual provides technical guidance for highway and materials engineers, waste and by-product generators, and others involved in making decisions regarding the use of waste and by-product materials in highway construction.

The manual covers nineteen waste and by-product materials from the domestic, industrial, and mining sectors and six high-volume pavement construction applications. For each material, information on material origin, sources, and properties is provided. In addition, application-specific information (for specific material-application combinations) is provided, including past performance, engineering properties, processing requirements, design and construction, and unresolved issues. General guidance on environmental and cost issues, and a general outline on determining the suitability of a material in an application, are also provided. The manual is distributed in loose-leaf format for ease of use and to allow future updates and expansion.

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waste materials, by-products, pavement construction, concrete, asphalt, stabilized base, granular base, embankment, fill

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**	**Symbol**	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	square millimeters	mm^2	mm^2	square millimeters	0.0016	square inches	in^2
ft^2	square feet	0.093	square meters	m^2	m^2	square meters	10.764	square feet	ft^2
yd^2	square yards	0.836	square meters	m^2	m^2	square meters	1.195	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	square kilometers	km^2	km^2	square kilometers	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	cubic meters	m^3	m^3	cubic meters	35.71	cubic feet	ft^3
yd^3	cubic yards	0.765	cubic meters	m^3	m^3	cubic meters	1.307	cubic yards	yd^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.									
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.202	pounds	lb
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")	Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C	°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION					**ILLUMINATION**		
fc	foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2	cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS					**FORCE and PRESSURE or STRESS**		
lbf	poundforce	4.45	newtons	N	N	newtons	0.225	poundforce	lbf
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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INTRODUCTION

PURPOSE

As the volume of waste and by-product materials generated in our society and the cost of disposal continue to increase, there is increased pressure and incentive to recover and recycle these materials for use in secondary applications. Because the construction of pavements requires large volumes of materials, highway agencies have become participants in these recycling efforts.

From a pavement engineering perspective, recovered materials should be used in such a manner that the expected performance of the pavement will not be compromised. Waste and by-product materials, however, differ vastly in their types and properties and, as a result, in the pavement applications for which they may be suited. Experience and knowledge regarding the use of these materials vary from material to material as well as from state to state. To recover these materials for potential use, engineers, researchers, generators, and regulators need to be aware of the properties of the materials, how they can be used, and what limitations may be associated with their use.

The primary purpose of this guideline document is to assist those who have an interest in using or increasing their understanding of the types of waste and by-product materials that may be recovered and used in pavement construction applications. It is intended to provide the potential user or reviewer with sufficient information on each material included in this document so that he or she will have an understanding of the nature of the material, where other information may be obtained, and what issues need to be evaluated when considering its use. It is also intended to provide the reader with general guidance on engineering evaluation requirements, environmental issues, and economic considerations for determining the suitability of using recovered materials in pavement applications.

Because of the ongoing development and publication of new information regarding the use of recovered materials in highway applications, this document has been designed in a looseleaf format to permit periodic revisions and updates.

SCOPE

These guidelines cover the use of waste and byproduct materials in six major highway construction applications: (1) Asphalt Concrete; (2) Portland Cement Concrete; (3) Granular Base; (4) Embankment or Fill; (5) Stabilized Base; and (6) Flowable Fill. In each of these primary application categories, there is at least one possible material use, and in some cases there are several potential uses. For example, in Portland Cement Concrete, a material may be used as aggregate or as a supplementary cementitious material. Table 1-1 lists the primary applications and the types of material uses in each respective application.

Table 1-1. Highway and pavement applications and material uses.

Asphalt Concrete Aggregate – Hot Mix Asphalt – Cold Mix Asphalt – Seal Coat or Surface Treatment Asphalt Cement Modifier Mineral Filler
Portland Cement Concrete Aggregate Supplementary Cementitious Materials
Granular Base
Embankment or Fill
Stabilized Base Aggregate Cementitious Materials – Pozzolan – Pozzolan Activator – Self-Cementing Material
Flowable Fill Aggregate Cementitious Materials – Pozzolan – Pozzolan Activator – Self-Cementing Material

This document includes guidelines for 19 waste and by-product materials. Listed in alphabetical order, they include: (1) Baghouse Fines; (2) Blast Furnace Slag; (3) Coal Bottom Ash/Boiler Slag; (4) Coal Fly Ash; (5) Flue Gas Desulfurization (FGD) Scrubber Material; (6) Foundry Sand; (7) Kiln Dusts; (8) Mineral Processing Wastes; (9) Municipal Solid Waste (MSW) Incinerator Ash; (10) Nonferrous Slags; (11) Quarry By-Products; (12) Reclaimed Asphalt Pavement; (13) Reclaimed Concrete Material; (14) Roofing Shingle Scrap; (15) Scrap Tires; (16) Sewage Sludge Ash; (17) Steel Slag; (18) Sulfate Wastes; and (19) Waste Glass.

The materials listed above do not represent the entire population of materials that have potential use in pavement construction applications. These 19 materials were selected based on the amount of the material generated as well as whether adequate data were available to prepare a description of the physical and chemical properties of the material and to describe the design requirements and performance records for one or more specific applications.

For the 19 materials and 6 major application categories, a total of 55 material-application combinations were selected and are included in these guidelines. Table 1-2 provides a listing of these 55 combinations. The omission of a particular material-application match in these guidelines is not to be construed as a prohibition against its use; rather, omission merely indicates that the authors felt that either the material-application combination was inappropriate or that insufficient information was available to provide a useful guideline.

The major portion of this document presents, for each of the 19 materials, a description of the material and user guidelines that includes the applications listed in Table 1-2.

Table 1-2. Application—material matrix.

APPLICATION – USE	MATERIAL
Asphalt Concrete – Aggregate (Hot Mix Asphalt)	Blast Furnace Slag Coal Bottom Ash Coal Boiler Slag Foundry Sand Mineral Processing Wastes Municipal Solid Waste Combustor Ash Nonferrous Slags Reclaimed Asphalt Pavement Roofing Shingle Scrap Scrap Tires Steel Slag Waste Glass
Asphalt Concrete – Aggregate (Cold Mix Asphalt)	Coal Bottom Ash Reclaimed Asphalt Pavement
Asphalt Concrete – Aggregate (Seal Coat or Surface Treatment)	Blast Furnace Slag Coal Boiler Slag Steel Slag
Asphalt Concrete – Mineral Filler	Baghouse Dust Sewage Sludge Ash Cement Kiln Dust Lime Kiln Dust Coal Fly Ash

Table 1-2. Application—material matrix (continued).

APPLICATION – USE	MATERIAL
Asphalt Concrete – Asphalt Cement Modifier	Roofing Shingle Scrap Scrap Tires
Portland Cement Concrete – Aggregate	Reclaimed Concrete
Portland Cement Concrete – Supplementary Cementitious Materials	Coal Fly Ash Blast Furnace Slag
Granular Base	Blast Furnace Slag Coal Bottom Ash Coal Boiler Slag Mineral Processing Wastes Municipal Solid Waste Combustor Ash Nonferrous Slags Reclaimed Asphalt Pavement Reclaimed Concrete Steel Slag Waste Glass
Embankment or Fill	Coal Fly Ash Mineral Processing Wastes Nonferrous Slags Reclaimed Asphalt Pavement Reclaimed Concrete Scrap Tires
Stabilized Base – Aggregate	Coal Bottom Ash Coal Boiler Slag
Stabilized Base – Cementitious Materials (Pozzolan, Pozzolan Activator, or Self-Cementing Material)	Coal Fly Ash Cement Kiln Dust Lime Kiln Dust Sulfate Wastes
Flowable Fill – Aggregate	Coal Fly Ash Foundry Sand Quarry Fines
Flowable Fill – Cementitious Material (Pozzolan, Pozzolan Activator, or Self-Cementing Material)	Coal Fly Ash Cement Kiln Dust Lime Kiln Dust

In addition to material-specific guidelines, several chapters of the report are devoted to recommended evaluation procedures for assessing whether a material is suitable for use in a designated application and to the environmental and cost issues that need to be considered when evaluating the use of waste and by-product materials in pavement construction. Finally, summary descriptions of the six pavement construction applications are presented to assist those readers who are interested in additional information relative to their design objectives and material uses.

ORGANIZATION AND CONTENT

This document is divided into 24 chapters. The contents of the chapters are described below.

Introduction

Chapter 1, the Introduction, provides an overview of the purpose, scope, and organization of this document.

Material-Specific Guidelines

Chapters 2 through 20 present the material-specific guidelines, one for each of the 19 materials included in the document. Each of these chapters contains a Material Description section and one or more User Guideline section(s).

The Material Description sections are divided into five subsections: (1) Origin; (2) Current Management Options; (3) Market Sources; (4) Highway Uses and Processing Requirements; and (5) Material Properties.

Origin: The Origin subsection presents a general description of the material, its industrial origin, the quantity of material generated annually in the United States, and other sources of information (e.g., trade associations) on the subject material.

Current Management Options: The Current Management Options subsection provides a description of present recycling and disposal practices.

Market Sources: The Market Sources subsection identifies locations or suppliers from whom the material can be obtained and special characteristics of the material that should be of interest to a prospective recycler.

Highway Uses and Processing Requirements: The Highway Uses and Processing Requirements subsection describes highway uses for which the material may have some proven or potential application as well as processing requirements that will be needed prior to use.

Material Properties: The Material Properties subsection provides a description of the physical, chemical, mechanical, and other properties that should be of interest to a prospective recycler.

Each User Guideline section is divided into seven subsections: (1) Introduction; (2) Performance Record; (3) Material Processing Requirements; (4) Engineering Properties; (5) Design Considerations; (6) Construction Procedures; and (7) Unresolved Issues.

Introduction: the Introduction subsection of each User Guideline presents a description of the role of the material in the designated application.

Performance Record: The Performance Record subsection describes the extent of prior experience and the advantages and disadvantages of using the material in the designated application.

Material Processing Requirements: The Material Processing Requirements subsection outlines the processing needs (e.g., cleaning, crushing, screening, etc.) that are required prior to use of the material in the designated application.

Engineering Properties: The Engineering Properties subsection presents a description of the properties that will be of particular interest to a prospective recycler who is considering the use of the material in the designated application.

Design Considerations: The Design Considerations subsection outlines the relevant mix design and structural design issues that are of interest when using the material in the designated application.

Construction Procedures: The Construction Procedures subsection describes special material handling, storage, mixing, curing, and placement issues that can arise when using the material in the designated application.

Unresolved Issues: The Unresolved Issues subsection summarizes important issues that are either unknown or need to be studied further to assist in making more widespread use of the material possible in the designated application.

Evaluation Guidance

Chapters 21, 22, and 23 are Evaluation Guidance chapters. Chapter 21 outlines a recommended framework for evaluating waste and by-product materials for use in pavement construction applications. It includes a description of the major steps that should be included in any evaluation process. The chapter is organized to address the requirements of each of the steps in this process.

Chapter 22 provides guidance relative to the environmental issues that a prospective recycler should be cognizant of when considering the use of waste and by-product materials in pavement construction applications. It includes a description of legislation and regulations that could have an impact on waste and by-product material use and outlines procedures that are available to assess potential health, environmental, and ecological impacts associated with the use of waste and by-product materials in pavement construction applications.

Chapter 23 provides guidance relative to economic issues that a prospective recycler or evaluator should consider when considering the use of waste and by-product materials in construction applications. It includes a description of recommended methods for calculating the cost of a recovered material, the cost of installation when incorporating a recovered material into a pavement, and the life cycle cost of the product when using a recovered material in pavement construction applications.

Application Descriptions

Chapter 24 It contains descriptions of the six applications listed in Table 1-1, and is intended for the reader who is interested in more detailed information about these applications. Each section of this chapter includes a general description of the application, a description of conventional materials typically used in the application and the desirable properties of those materials, and a description of the testing methods that are commonly used to evaluate the properties of these materials as they pertain to the designated application.

ORIGIN

Hot mix asphalt baghouse fines are dust particles that are captured from the exhaust gases of asphalt mixing plants. Secondary collection equipment called baghouses are commonly used to capture these very fine sized materials.

There are approximately 3,600 hot mix asphalt plants in the United States, accounting for a total annual production of 400 to 450 million metric tons (450 to 500 million tons) of asphalt paving material. About 2,300 of these hot mix plants are batch plants, with the remaining 1,300 being drum mix plants. Roughly 40 to 50 percent of all hot mix asphalt plants are equipped with baghouse collections systems. Baghouses consist of several rows or compartments of fabric filters that collect the dust during the operation of a hot mix asphalt plant. Most of these systems are preceded by cyclones, which are primary collection devices used to capture the coarser particles emitted from the plant's dryer. Hot mix plants that do not have baghouse collection systems are equipped with wet scrubbers to control air emissions.

Drum mix and batch plants differ in their asphalt concrete production operations. In drum mix plants presized cold aggregates are fed into a drum, in accordance with preselected mix design proportions. The aggregates are dried and mixed with asphalt cement, which is introduced at the end of the drum (coating zone), in a continuous process. In batch plants unsorted aggregates are introduced into a dryer and subsequently screened into different size fractions, stored (in hot bins), and fed, by batch weight, into a separate pugmill mixer where the hot aggregates are mixed with asphalt cement.

Simplified line diagrams of batch and drum mix plant operations are presented in Figure 2-1. Baghouse fines collected in the baghouse may be routed directly to the asphalt production facility or stored in a silo for subsequent use as a mineral filler additive in the mix.

It is estimated that approximately 5.4 to 7.2 million metric tons (6 to 8 million tons) of baghouse fines are generated annually by the U.S. asphalt production industry.(1)

Additional information on the use of baghouse fines can be obtained from:

National Asphalt Paving Association (NAPA)
5100 Forbes Boulevard
Lanham, Maryland 20706

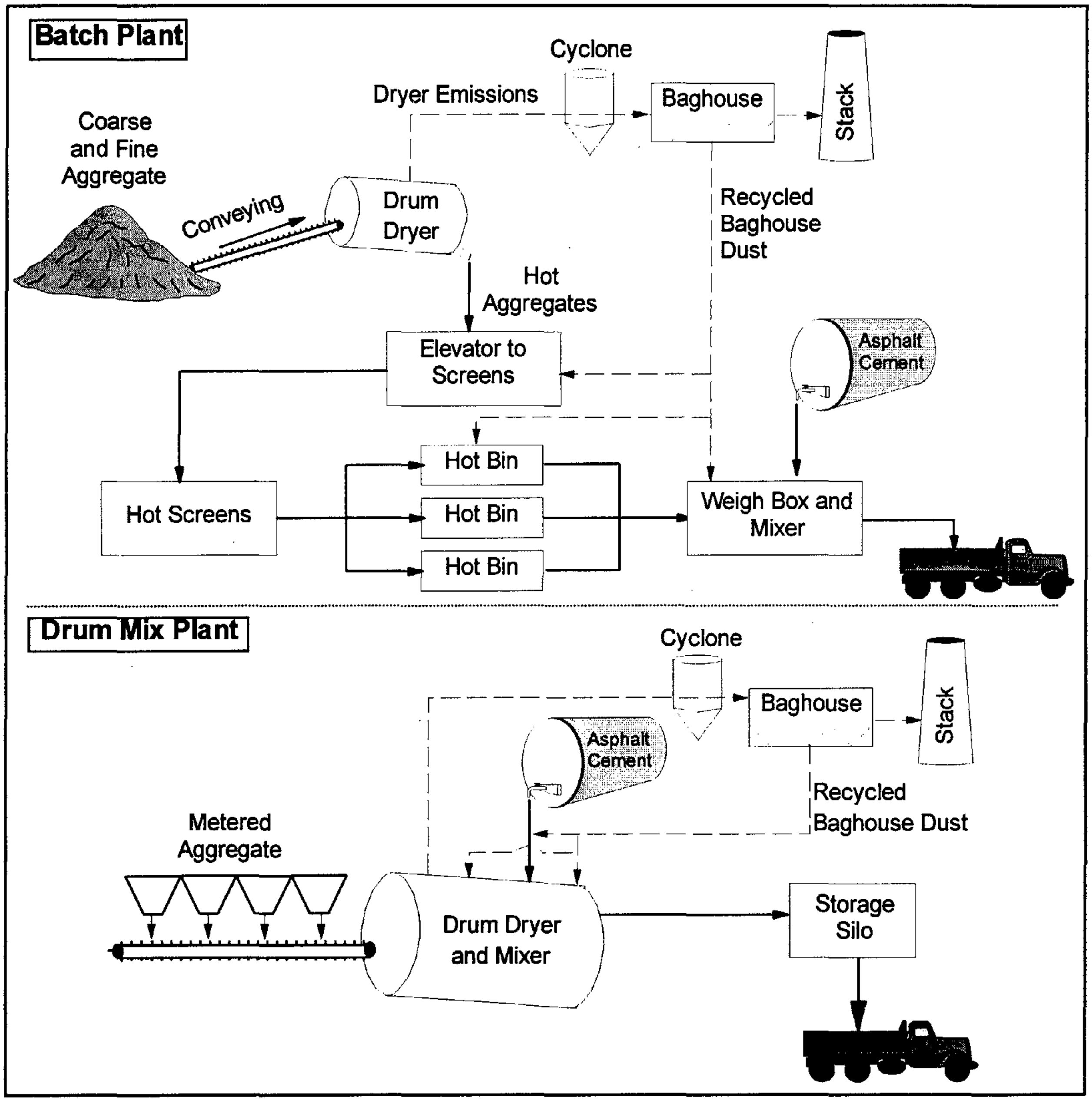

Figure 2-1. Batch plant and drum mix plant operations.

CURRENT MANAGEMENT OPTIONS

Recycling

Most asphalt producers whose plants are equipped with baghouses try to recycle as much of the dust back into their own paving mixes as possible. Although precise figures are not available, it is estimated that as much as 80 to 90 percent of baghouse fines are currently being recycled into hot mix asphalt.

Disposal

Although most of the baghouse fines are returned to the asphalt mixing plant, some producers (probably less than 10 percent) with excess dust dispose of the dust by sluicing it to a settling pond or returning it to the quarry.(2) Where wet scrubbers are employed for dust control instead of baghouses, the washed fines are generally discarded.

MARKET SOURCES

Baghouse fines are almost exclusively recycled within the asphalt production facility.

The properties of baghouse fines that might be obtained from an asphalt production facility are influenced by the sizing and moisture content of the cold feed aggregates, the type of aggregate feed material(s), the type of asphalt plant (batch or drum mix), and the design of the dust collection and handling system.

Although baghouse dusts are frequently referred to as baghouse fines, there can be a considerable variation in the fineness of baghouse dusts from one plant to another. This variability is related mainly to the efficiency of the primary collection (i.e., cyclone, if available) system and the nature of the cold feed aggregate. The percentage of material in the cold feed that passes the 0.6 mm (No. 30) sieve is important, since aggregate particles as coarse as the 0.6 mm (No. 30) sieve can be entrained in the exhaust gas.(2)

HIGHWAY USES AND PROCESSING REQUIREMENTS

Asphalt Concrete Mineral Filler

The only established use for baghouse fines or dust is the return of the dust into an asphalt paving mixture as a portion of or, in some cases, all of the mineral filler. Mineral fillers can constitute up to 5 percent of some asphalt pavements.

MATERIAL PROPERTIES

Physical Properties

Although baghouse fines are usually very fine-grained, plants without a primary collector or cyclone have retained from 0.8 to 5.8 percent of the dust on a 0.6 mm (No. 30) sieve. This is about the expected maximum particle size of baghouse fines.(2)

The size distribution of baghouse fines consists of a coarse fraction and a fine fraction, with the dividing size being the 0.075 mm (No. 200) sieve. There can be a considerable range in the percentage of dust particles passing the 0.075 mm (No. 200) sieve. Plants without a primary collection system often collect dust with less than 50 percent of the material collected passing the 0.075 mm (No. 200) sieve. On the other hand, more than half of the plants with a primary collection system collect dust with 90 to 100 percent of the particles finer than the 0.075 mm (No. 200) sieve.(2)

Other relevant physical properties of baghouse fines are specific gravity, specific surface, hygroscopic moisture, and Atterberg limits. Table 2-1 summarizes the observed range of values for the physical properties of baghouse fines. With few exceptions, baghouse fines normally absorb less than 2 percent moisture at 50 percent relative humidity. Baghouse fines contain little or no clay and will generally have little or no trouble meeting the plasticity requirement for mineral filler, which limits the plasticity index value to 4.0.(2)

Table 2-1. Typical range of physical properties of baghouse dusts.

Range	Gradation (Percent Passing)				Specific Gravity	Specific Surface* m^2/g	Hygroscopic Moisture (%)	Liquid Limit	Plasticity Index
	0.600 mm (No. 30 sieve)	0.300 mm (No. 50 sieve)	0.075 mm (No. 200 sieve)	0.01 mm					
Maximum	100	100	100	78	2.87	2.18	1.9	39	4
Minimum	95	82	28	4	2.57	0.06	0.2	NL	NP

*Measured by air permeability NL = Nonliquid; NP = nonplastic

Chemical Properties

With few exceptions, the pH of baghouse fines is alkaline, with values ordinarily ranging from 7.2 to 10.8 for dusts from gravel, granite, or traprock aggregates and values ranging from 11.0 to

12.4 for dusts from limestone and dolomite aggregates. The chemical properties of baghouse dust can be expected to reflect the properties of the feed aggregate.

REFERENCES

1. Collins, Robert J. and Stanley K. Ciesielski. *Recycling and Use of Waste Materials and By-Products in Highway Construction.* National Cooperative Highway Research Program Synthesis of Highway Practice No. 199, Transportation Research Board, Washington, DC, 1994.

2. American Association of State Highway and Transportation Officials. Standard Method of Test, "Mineral Filler for Bituminous Paving Mixtures," AASHTO Designation: M17-83, Part I Specifications, 14th Edition, 1986.

INTRODUCTION

Baghouse fines from dust collection devices at asphalt mixing plants are routinely recycled as all or part of the mineral filler portion in hot mix asphalt paving mixtures. Since these fines are derived from naturally occurring aggregates (crushed stone or sand and gravel), their properties are ordinarily quite similar to those of commonly used mineral fillers, such as stone dust or hydrated lime. Baghouse fines from a particular plant and aggregate type should only be used at that plant and with the aggregate type from which it was derived, since baghouse fines from different aggregates vary in gradation, chemical composition, and affinity for asphalt.

PERFORMANCE RECORD

There is a limited amount of documented field performance data related to the use of baghouse dust as a mineral filler. Between 1975 and 1980, the Pennsylvania Department of Transportation (PennDOT) monitored the performance of 12 pavement sections in western Pennsylvania that contained different sources of baghouse fines. Examination of core samples from these pavements indicated that unusually high or inconsistent incorporation of baghouse fines resulted in mixes that were stiff, brittle, and difficult to compact.(1)

Furthermore, a number of the mixes monitored exhibited high air voids contents that accelerated asphalt hardening and contributed to premature distress in the form of ravelling, loss of fines, and reduced pavement durability. These problems appeared to be more prevalent when baghouse fines from slag aggregates were used, compared with baghouse fines from crushed stone aggregates. The pavement cores for projects using slag fines all showed an excessive amount of fines and high air voids contents (from 9 to 14 percent), which led to poor mix compaction and accelerated age hardening of the asphalt.(1)

A number of state transportation agencies and/or trade associations have also investigated the use of baghouse dust or baghouse fines as a mineral filler in asphalt mixtures. Many of these studies were laboratory investigations that focused on the variability of baghouse dust and the effect of such variability on mixture behavior.

In 1976, the California Department of Transportation studied the effects of six different sources of baghouse dust on Hveem mixture design parameters. The report concluded that a maximum baghouse fines content of 2.0 percent has little effect on the stability of asphalt mixtures and was found to be beneficial to mixture cohesion.(2)

In 1978, the Asphalt Institute evaluated the properties of asphalt mixtures containing baghouse fines from a number of sources. The properties of the mixes with baghouse fines were compared to known properties of commercial mineral fillers and filler-asphalt mixtures. Although significant variations in gradation were found in the dust sampled from different plants, it was concluded that the quality of baghouse fines is satisfactory for use in asphalt mixtures as long as the quality of the parent aggregate is satisfactory.(3)

The West Virginia Department of Highways studied 16 different sources of baghouse fines with a wide variety of particle size ranges and physical and chemical properties. The study found that fine dust particles (0.020 mm and smaller) will combine with the asphalt binder and act as an extender. The report concluded that baghouse dust is not harmful to a paving mixture and can be successfully reintroduced into an asphalt mixture.(4)

The Washington State Department of Transportation investigated the grain size distribution of 12 different baghouse dust sources and added 3 of those dusts to asphalt mixes. The gradation of the baghouse fines varied considerably from plant to plant. The viscosity of the dust-asphalt mixtures varied considerably, and temperature susceptibilities and hardening were different for the different dusts and the two asphalt cements. Little correlation was found between particle size and consistency of the dust-asphalt mixtures.(5)

MATERIAL PROCESSING REQUIREMENTS

Baghouse dust from the primary collection system (cyclone), if present, is generally returned to the hot elevator. Baghouse dust from the baghouse hopper can be returned to the hot elevator, the No. 1 hot bin, or the weigh box. In either case, the dust is dry and further processing is unnecessary.

ENGINEERING PROPERTIES

Some of the properties of baghouse fines that are of particular interest when baghouse fines are used as mineral filler in asphalt pavements include gradation, organic impurities, and plasticity index. Mineral filler requirements, which address these properties, are specified in American Association of State Highway and Transportation Officials (AASHTO) M17(6) and are shown in Table 2-2.

Gradation: Whether baghouse dust will comply with AASHTO gradation specifications depends largely on whether the asphalt plant is equipped with a primary dust collector (cyclone). The primary collector captures the coarser particles, thus ensuring that the remainder of the dust will be sufficiently well graded and fine enough to consistently satisfy AASHTO M17 gradation requirements.(7)

Table 2-2. AASHTO M17-83 specification requirements for mineral filler for use in bituminous paving mixtures.

Particle Sizing		Organic Impurities	Plasticity Index
Sieve Size	Percent Passing		
0.600 mm (No. 30)	100	Mineral filler must be free from any organic impurities	Mineral filler must have plasticity index not greater than 4
0.300 mm (No. 50)	95 - 100		
0.075 mm (No. 200)	70 - 100		

Organic Impurities: In a National Cooperative Highway Research Program (NCHRP) study on baghouse dust, little to no clay was found in 26 different baghouse dust samples. Organic impurities are seldom detected in baghouse dust, except possibly in asphalt plants that burn oil.(8)

Plasticity Index: In the same NCHRP study, the plasticity indices of 23 samples were all less than 4.(8)

The properties of the asphalt concrete that could be affected by baghouse dust include cement penetration and viscosity, stability, resilient modulus, and moisture sensitivity.

Penetration and Viscosity: Previous studies indicate that an increase in the fines/asphalt ratio (from 0.2 to 0.5 by volume) can be expected to result in an almost linear decrease in the penetration value of the resultant asphalt binder material.(7) The viscosity of fines/asphalt blends can be expected to increase or stiffen as the fines/asphalt ratio is increased.

Stability: The bulk volume of fines in a mix will have a direct effect on Marshall stability. As the fines/asphalt ratio increases, the Marshall stability can also be expected to increase, until peak stability is reached at or around 55 percent bulk volume of fines in the binder.(1)

Resilient Modulus: Laboratory tests indicate that the resilient modulus can be expected to increase with increasing dust content.(9)

Moisture Sensitivity: Moisture sensitivity is a possible concern in asphalt mixes in which baghouse fines are used as all or part of the mineral filler. It is recommended that the bulk volume of fines should be less than 50 percent in order to minimize the potential for moisture damage or stripping of dense graded asphalt paving mixtures.(1)

DESIGN CONSIDERATIONS

Mix Design

Asphalt mixes containing baghouse fines can be designed using standard laboratory procedures.

Moisture sensitivity of the design mixes, as determined in the laboratory, should be determined using the Marshall immersion-compression test (ASTM D1075), with a minimum 75 percent retained strength.(10)

The fines/asphalt ratio should be closely monitored during the mix design to limit the bulk volume of fines to less than 50 percent. The particle size distribution of the baghouse fines should be well-graded, with some of the dust finer than 0.010 to 0.020 mm. The percent free asphalt should be kept at approximately 40 percent, since excessive amounts of baghouse fines as filler are likely to result in an asphalt mix that will be difficult to compact. The fines/asphalt ratio is a better control criterion than seeking an upper limit or the percentage of baghouse fines in the mix.(16)

The asphalt mix design must also take into account the location (or locations) where the dust is being collected and added into the paving mix at the asphalt plant. If dust is being added from a primary collection device (such as a cyclone) and/or a baghouse, the relative proportions of dust collected from each source must be known beforehand and closely monitored during asphalt production to ensure that they remain consistent. The dust type and gradation have been found to have a significant influence on the mechanical properties of an asphalt mix. Well-graded dusts tend to behave in the most predictable manner. Anomalous behavior can be expected when the dust is highly uniform (one-sized) and finer than 0.010 to 0.015 mm, or when the dust is coarse and lacking material finer than 0.010 to 0.020 mm.(9)

The aggregate source from which the baghouse dust is derived may also have an effect on asphalt binder properties. Baghouse fines from gneiss, traprock, sand and gravel, and slag aggregates were reported to result in larger viscosity increases (and corresponding decreases in ductility) when introduced at a high fines/asphalt ratio (0.3 to 0.5) than fines from carbonate aggregates.(7) The bulk volume concentration of fines in the fines/asphalt system, however, appears to be the primary factor causing stiffening of the asphalt binder.(1)

Structural Design

Conventional AASHTO pavement structural design methods are appropriate for asphalt pavements containing baghouse fines.

CONSTRUCTION PROCEDURES

Material Handling and Storage

Baghouse dust can be fed directly from the baghouse into the plant mix or stored in a silo prior to use. The location where the baghouse fines are to be added to the plant mix depends on whether the plant is a batch mixing plant or a drum mix plant. In many cases, baghouse dust may be only a part of the mineral filler component of the mixture.

In a batch mixing plant, baghouse fines can be returned to the paving mix at three different locations: (1) the hot elevator, (2) the No. 1 hot bin, or (3) the weigh box. The preferred method is direct return of the dust to the hot elevator or the No. 1 hot bin, if proper control of uniformity can be obtained. A surge bin and a positive feed system may be added to improve metering uniformity. If these systems do not ensure uniformity in the quantity of fines, it may be necessary to meter the dust into the weigh hopper.(11)

In a drum mix plant, baghouse dust can be returned at one of four possible locations: (1) the cold feed conveyor, (2) the drum entrance, (3) the drum discharge, or (4) at the point where the asphalt cement is introduced. This latter location is the location that has been most widely recommended by state transportation agencies and manufacturers of drum mix plants.(7) The introduction of the dust simultaneously with the asphalt cement eliminates re-entrainment of the dust in the system gas and provides a good distribution of the dust through the coating zone. If the dust is introduced to the cold feed or at the drum entrance, it may be recycled through the system gas. The least desirable method is blowing the dust into the mixture at the drum discharge. Introduction of the dust together with the asphalt cement is the recommended method and is also the most widely accepted by state highway agencies and manufacturers of drum mix plants.(7)

Mixing, Placing, and Compacting

The same methods and equipment used to mix, place, and compact conventional asphalt paving mixes are applicable for mixes containing baghouse fines. However, if the filler/asphalt ratio with baghouse fines is too high, a stiffer mix may result and the specified level of compaction may be difficult to obtain. Inadequate compaction appears to be more of a problem when very fine baghouse fines are used as filler.

Quality Control

The same field testing procedures used for conventional hot mix asphalt mixes should be used for mixes containing baghouse fines. Mixes should be sampled in accordance with AASHTO T168,(12) and tested for specific gravity in accordance with ASTM D2726(13) and in-place density in accordance with ASTM D2950.(14)

UNRESOLVED ISSUES

There are wide variations in the stiffening effects of baghouse fines, which are not fully explained by either the fineness or the gradation of a particular dust source. The effect of dusts from different types of aggregates on the compactibility of asphalt concrete mixtures needs to be more fully understood. The influence of the stiffening effect of baghouse fines on the fatigue and mechanical properties of asphalt paving mixtures also requires further study.

The range of dust properties that enhance asphalt extension and the effects of asphalt extension on the stiffness, fatigue, and aging characteristics of the asphalt cement binder are also worthy of investigation.(7)

There is some concern that the introduction of baghouse fines without a proper check on the design properties of the mix could possibly be a cause of tender mixes.(15) Tender mixes are characterized in one of two ways. One is that the asphalt mix is difficult to compact when normal construction techniques are used, which is usually manifested by shoving of the material under a steel wheel roller. The other type of tenderness relates to the slow setting of the asphalt mixture after placement, making it sensitive to wheel turning or concentrated loading, especially during periods of hot weather.(16) Some further investigation of this concern may be warranted.

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ORIGIN

In the production of iron, iron ore, iron scrap, and fluxes (limestone and/or dolomite) are charged into a blast furnace along with coke for fuel. The coke is combusted to produce carbon monoxide, which reduces the iron ore to a molten iron product. This molten iron can be cast into iron products, but is most often used as a feedstock for steel production.

Blast furnace slag is a nonmetallic coproduct produced in the process. It consists primarily of silicates, aluminosilicates, and calcium-alumina-silicates. The molten slag, which absorbs much of the sulfur from the charge, comprises about 20 percent by mass of iron production. Figure 3-1 presents a general schematic which depicts the blast furnace feedstocks and the production of blast furnace coproducts (iron and slag).

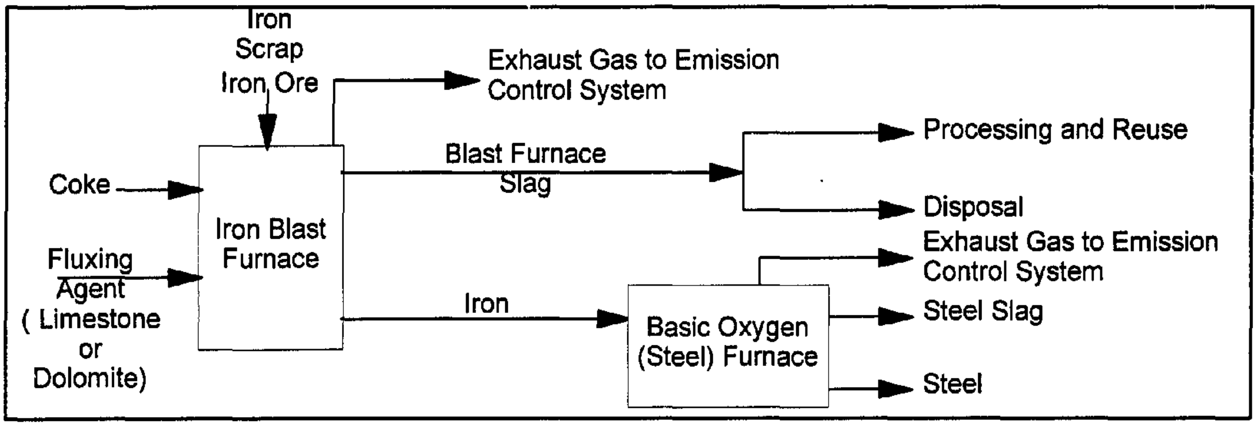

Figure 3-1. General schematic of blast furnace operation and blast furnace slag production.

Different forms of slag product are produced depending on the method used to cool the molten slag. These products include air-cooled blast furnace slag (ACBFS), expanded or foamed slag, pelletized slag, and granulated blast furnace slag.

Air-Cooled Blast Furnace Slag

If the liquid slag is poured into beds and slowly cooled under ambient conditions, a crystalline structure is formed, and a hard, lump slag is produced, which can subsequently be crushed and screened.

Expanded or Foamed Blast Furnace Slag

If the molten slag is cooled and solidified by adding controlled quantities of water, air, or steam, the process of cooling and solidification can be accelerated, increasing the cellular nature of the slag and producing a lightweight expanded or foamed product. Foamed slag is distinguishable from air-cooled blast furnace slag by its relatively high porosity and low bulk density.

Pelletized Blast Furnace Slag

If the molten slag is cooled and solidified with water and air quenched in a spinning drum, pellets, rather than a solid mass, can be produced. By controlling the process, the pellets can be made more crystalline, which is beneficial for aggregate use, or more vitrified (glassy), which is more desirable in cementitious applications. More rapid quenching results in greater vitrification and less crystallization.

Granulated Blast Furnace Slag

If the molten slag is cooled and solidified by rapid water quenching to a glassy state, little or no crystallization occurs. This process results in the formation of sand size (or frit-like) fragments, usually with some friable clinkerlike material. The physical structure and gradation of granulated slag depend on the chemical composition of the slag, its temperature at the time of water quenching, and the method of production. When crushed or milled to very fine cement-sized particles, ground granulated blast furnace slag (GGBFS) has cementitious properties, which make a suitable partial replacement for or additive to Portland cement.

It is estimated that approximately 14 million metric tons (15.5 million tons) of blast furnace slag is produced annually in the United States.(1)

Additional information on processed blast furnace slag use in the United States can be obtained from:

National Slag Association
808 North Fairfax Street
Alexandria, Virginia 22314

CURRENT MANAGEMENT OPTIONS

Recycling

Almost all of the blast furnace slag produced in the United States is reportedly utilized, and approximately 90 percent of this slag is ACBFS. The proportion of ACBFS currently being produced, however, is decreasing relative to granulated and pelletized blast furnace slag production.(2) The production of expanded blast furnace slag is no longer favored and is being replaced by the pelletizing procedure.

ACBFS has been used as an aggregate in Portland cement concrete, asphalt concrete, and road bases. Pelletized blast furnace slag has been used as lightweight aggregate and for cement manufacture. Foamed slag has been used as a lightweight aggregate for Portland cement concrete. Granulated blast furnace slag has been used as a raw material for cement production and as an aggregate and insulating material. ACBFS and granulated slag have also been used as sandblasting shot materials. Ground granulated blast furnace slag is used commercially as a supplementary cementitious material in Portland cement concrete (as a mineral admixture or component of blended cement).

Disposal

It is estimated that a relatively small percentage (less than 10 percent) of the blast furnace slag generated is disposed of in landfills.

MARKET SOURCES

Blast furnace slag materials are generally available from slag processors located near iron production centers.

Cements containing ground granulated blast furnace slag are available from many producers of Portland cement or directly from ground granulated blast furnace slag cement manufacturers. AASHTO M240 describes three types of blended cements containing slag.(3) They include Portland blast furnace slag cement (Type IS), slag modified Portland cement (Type I (SM)), and slag cement (Type S). The primary distinction among the three types is the percentage of slag they contain. Slag cement may contain Portland cement or hydrated lime (or both) while the other two are blends of Portland cement and slag only.

HIGHWAY USES AND PROCESSING REQUIREMENTS

ACBFS - Aggregate Substitute

Many specifying agencies consider ACBFS to be a conventional aggregate. It is extensively used in granular base, hot mix asphalt, Portland cement concrete, and embankments or fill applications. The material can be crushed and screened to meet specified gradation requirements using conventional aggregate processing equipment. Special quality control procedures may be required to address the lack of consistency in some properties such as gradation, specific gravity, and absorption.

GGBFS and Vitrified Pelletized BFS — Supplementary Cementitious Materials

GGBFS is used as a mineral admixture for Portland cement concrete. Granulated blast furnace slag and vitrified pelletized blast furnace slag are also used in the manufacture of blended hydraulic cements (AASHTO M240).(3) When used in blended cements, granulated blast furnace slag or vitrified pelletized slag are milled to a fine particle size in accordance with AASHTO M302 requirements.(4) The ground slag can be introduced and milled with the cement feedstock or blended separately after the cement is ground to its required fineness.

The U.S. Environmental Protection Agency (EPA) has recommended that effective May 1, 1995, procuring agencies specifically include provision in all construction contracts for the use of GGBFS in Portland cement concrete contracts.(5)

MATERIAL PROPERTIES

Physical Properties

Table 3-1 lists some typical physical properties of air-cooled, expanded, and pelletized blast furnace slags.

Table 3-1. Typical physical properties of blast furnace slag.(6)

Property	Slag Type and Value		
	Air-Cooled(6)	Expanded(6,7)	Pelletized(7)
Specific Gravity	2.0 - 2.5	—	—
Compacted Unit Weight, kg/m^3 (lb/ft^3)	1120 - 1360 (70 - 85)	800 - 1040 (50 - 65)	840 (52)
Absorption (%)	1 - 6	—	—

Air-Cooled Blast Furnace Slag

Crushed ACBFS is angular, roughly cubical, and has textures ranging from rough, vesicular (porous) surfaces to glassy (smooth) surfaces with conchoidal fractures. There can, however, be considerable variability in the physical properties of blast furnace slag, depending on the iron production process. For example, some recently produced ACBFS was reported to have a compacted unit weight as high as 1940 kg/m^3 (120 lb/ft^3).(8) Higher unit weights that are reported are generally due to increased metals and iron content in the slag and tend to occur in slags that are generated from blast furnaces with higher scrap metal additions.

The water absorption of ACBFS can be as high as 6 percent. Although ACBFS can exhibit these high absorption values, ACBFS can be readily dried since little water actually enters the pores of the slag and most is held in the shallow pits on the surface.

Expanded Blast Furnace Slag

Crushed expanded slag is angular, roughly cubical in shape, and has a texture that is rougher than that of air-cooled slag. The porosity of expanded blast furnace slag aggregates is higher than ACBFS aggregates. The bulk relative density of expanded slag is difficult to determine accurately, but it is approximately 70 percent of that of air-cooled slag. Typical compacted unit weights for expanded blast furnace slag aggregates range from 800 kg/m^3 (50 lb/ft^3) to 1040 kg/m^3 (65 lb/ft^3).(6)

Pelletized Blast Furnace Slag

Unlike air-cooled and expanded blast furnace slag, pelletized blast furnace slag has a smooth texture and rounded shape. Consequently, the porosity and water absorption are much lower than those of ACBFS or expanded blast furnace slag. Pellet sizes range from 13 mm (1/2 in) to 0.1 mm (No. 140 sieve size), with the bulk of the product in the minus 9.5 mm (3/8 in) to plus 1.0 mm (No. 18 sieve size) range. Pelletized blast furnace slag has a unit weight of about 840 kg/m^3 (52 lb/ft^3).(7)

Granulated Blast Furnace Slag

Granulated blast furnace slag is a glassy granular material that varies, depending on the chemical composition and method of production, from a coarse, popcornlike friable structure greater than 4.75 mm (No. 4 sieve) in diameter to dense, sand-size grains passing a 4.75 mm (No. 4) sieve. Grinding reduces the particle size to cement fineness, allowing its use as a supplementary cementitious material in Portland cement concrete.

Chemical Properties

Table 3-2 depicts the typical chemical composition of blast furnace slag. The chemical compositions shown are in general applicable to all types of slag. The data presented in Table 3-2 suggest that the chemical composition of blast furnace slags produced in North America has remained relatively consistent over the years.

Table 3-2. Typical composition of blast furnace slag.(9)

Constituent	Percent							
	1949[a]		1957[a]		1968[a]		1985[a]	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Calcium Oxide (CaO)	41	34 – 48	41	31– 47	39	32 – 44	39	34 – 43
Silicon Dioxide (SiO_2)	36	31– 45	36	31– 44	36	32 – 40	36	27 – 38
Aluminum Oxide (Al_2O_3)	13	10 – 17	13	8 – 18	12	8 – 20	10	7 – 12
Magnesium Oxide (MgO)	7	1 – 15	7	2 – 16	11	2 – 19	12	7 – 15
Iron (FeO or Fe_2O_3)	0.5	0.1 – 1.0	0.5	0.2 – 0.9	0.4	0.2 – 0.9	0.5	0.2 – 1.6
Manganese Oxide (MnO)	0.8	0.1 – 1.4	0.8	0.2 – 2.3	0.5	0.2 – 2.0	0.44	0.15 – 0.76
Sulfur (S)	1.5	0.9 – 2.3	1.6	0.7 – 2.3	1.4	0.6 – 2.3	1.4	1.0 – 1.9

a. Data source is the National Slag Association data: 1949 (22 sources); 1957 (29 sources); 1968 (30 sources) and 1985 (18 sources).

When ground to the proper fineness, the chemical composition and glassy (noncrystalline) nature of vitrified slags are such that when combined with water, these vitrified slags react to form cementitious hydration products. The magnitude of these cementitious reactions depends on the chemical composition, glass content, and fineness of the slag. The chemical reaction between GGBFS and water is slow, but it is greatly enhanced by the presence of calcium hydroxide, alkalies and gypsum ($CaSO_4$).

Because of these cementitious properties, GGBFS can be used as a supplementary cementitious material either by premixing the slag with Portland cement or hydrated lime to produce a blended cement (during the cement production process) or by adding the slag to Portland cement concrete as a mineral admixture.

Blast furnace slag is mildly alkaline and exhibits a pH in solution in the range of 8 to 10. Although blast furnace slag contains a small component of elemental sulfur (1 to 2 percent), the leachate tends to be slightly alkaline and does not present a corrosion risk to steel in pilings(10) or to steel embedded in concrete made with blast furnace slag cement or aggregates.(11)

In certain situations, the leachate from blast furnace slag may be discolored (characteristic yellow/green color) and have a sulfurous odor. These properties appear to be associated with the presence of stagnant or slow-moving water that has come in contact with the slag. The stagnant water generally exhibits high concentrations of calcium and sulfide, with a pH as high as 12.5.(12) When this yellow leachate is exposed to oxygen, the sulfides present react with oxygen to precipitate white/yellow elemental sulfur and produce calcium thiosulfate, which is a clear solution. (See references 13,14,15,16,17,18,19.) Aging of blast furnace slag can delay the formation of yellow leachate in poor drainage conditions but does not appear to be a preventative measure, since the discolored leachate can still form if stagnant water is left in contact with the slag for an extended period.(12)

Mechanical Properties

Of all the slag types generated, air-cooled blast furnace is the type that is most commonly used as an aggregate material. Processed ACBFS exhibits favorable mechanical properties for aggregate use including good abrasion resistance, good soundness characteristics, and high bearing strength. Table 3-3 provides a listing of typical mechanical properties of ACBFS aggregates.

Table 3-3. Typical mechanical properties of air-cooled blast furnace slag.(20)

Property	Value
Los Angeles Abrasion (ASTM C131)	35 – 45%
Sodium Sulfate Soundness Loss (ASTM C88)	12%
Angle of Internal Friction	40° – 45°
Hardness (measured by Moh's scale of mineral hardness)*	5 – 6
California Bearing Ratio (CBR), top size 19 mm (3/4 in)**	up to 250%
*Hardness of dolomite measured on same scale is 3 to 4 **Typical CBR value for crushed limestone is 100%	

Other Properties

Because of their more porous structure, blast furnace slag aggregates have lower thermal conductivities than conventional aggregates.(21) Their insulating value is of particular advantage in applications such as frost tapers (transition treatments in pavement subgrades between frost susceptible and nonfrost susceptible soils) or pavement base courses over frost-susceptible soils.

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INTRODUCTION

Air-cooled blast furnace slag (ACBFS) is considered by many specifying agencies to be a conventional aggregate and can replace both coarse and fine aggregates in asphalt paving applications. ACBFS, however, is more absorptive than conventional aggregate and therefore has a higher asphalt cement demand. It also has a lower compacted unit weight than conventional mineral aggregates, which results in a higher asphalt pavement yield (greater volume for the same weight).

PERFORMANCE RECORD

At least 17 states have specifications covering the use of ACBFS as aggregate in surface course hot mix asphalt. They include Alabama, Colorado, Florida, Illinois, Indiana, Kentucky, Louisiana, Michigan, New York, Ohio, Pennsylvania, Tennessee, Texas, Utah, Virginia, West Virginia, and Wisconsin.(1) Hot mix asphalt containing properly selected and processed ACBFS aggregates demonstrates good frictional resistance in pavement surfaces, good stripping resistance, and high stability.

The use of ACBFS aggregates in surface treatment applications has been accepted by many of the same jurisdictions that incorporate ACBFS aggregates in hot mix asphalt. Surface-treated pavements incorporating ACBFS aggregate demonstrate good friction resistance, good resistance to stripping, and fair wear resistance. However, the resistance of ACBFS to impact is not very high and the material can break down under heavy traffic conditions. Such aggregate is better suited to surface treatment applications on light traffic pavements.

Variability in the iron production process can result in a lack of consistency in the physical properties (gradation, specific gravity, absorption, and angularity) of ACBFS. This lack of consistency has occasionally contributed to hot mix asphalt performance problems, such as flushing due to high binder content (too rich), ravelling due to low binder content, and high fines to asphalt ratios (too lean).(2)

MATERIAL PROCESSING REQUIREMENTS

Material Quality Control

Hot mix asphalt and surface treatments require aggregates that exhibit consistent physical characteristics and quality. Special attention is required to address inconsistent physical properties of some ACBFS. More rigorous quality control is required in the selection and processing of ACBFS aggregates than conventional aggregates.

Crushing and Screening

Conventional aggregate crushing and screening operations are used to process ACBFS for use as an aggregate in asphalt concrete.

ENGINEERING PROPERTIES

Some of the engineering properties of ACBFS that are of particular interest when ACBFS is used as an aggregate in asphalt concrete include gradation, compacted density, absorption, abrasion, and freeze-thaw resistance.

Gradation: Blast furnace slag should be crushed and screened to produce aggregate that satisfies the gradation requirements for hot mix asphalt as specified in ASTM D692(3) for coarse aggregate and AASHTO M29(4) for fine aggregate. For surface treatments, ACBFS aggregate should satisfy ASTM D1139(5) gradation specification requirements.

Compacted Density: The compacted density of ACBFS ranges from 1120 kg/m^3 (70 lb/ft^3) to 1940 kg/m^3 (120 lb/ft^3), which is somewhat lower than that of conventional aggregates. Allowance for this differential should be considered during design and in specifications in order to ensure equal volume irrespective of the type of the aggregate used. Asphalt mixes incorporating blast furnace slag aggregates should be designed volumetrically.

Absorption: The vesicular (porous) surface texture of ACBFS contributes to higher absorption than conventional aggregates. High absorption leads to an increased asphalt cement requirement (up to 3 percent more by weight of mix), resulting in an increase in the cost of the ACBFS paving mixes relative to conventional mixes. This is offset somewhat by the higher yield (volume per mass) of ACBFS paving mixtures because of the lower unit weight of the mix.

Abrasion: Although the resistance to degradation of ACBFS aggregates as measured by the Los Angeles machine(6) is not particularly favorable (because the sharp edges break off), field performance has been satisfactory. Consequently, the ASTM testing requirement for degradation of ACBFS aggregates has been deleted from standard specifications for hot mix and surface treatment aggregates (see ASTM D692 and ASTM D1139). Major slag-using states, such as Michigan, Ohio, and Indiana, do not have Los Angeles Abrasion loss requirements for ACBFS.(7)

Freeze-Thaw Resistance: ACBFS displays good resistance to freeze-thaw weathering.(8)

Some of the properties of asphalt paving mixes that are of particular interest when ACBFS is incorporated into the mix include stability, frictional properties, resistance to rutting, and resistance to stripping.

Stability: The angular shape and high friction angle (40° to 45°) of crushed ACBFS contributes to good lateral stability when ACBFS is incorporated into paving mixes. This is particularly beneficial where hard braking and acceleration are considerations.

Frictional Properties: One of the more notable features of asphalt concrete containing ACBFS is its high frictional resistance.(9,10) This is due to the rough, vesicular surface texture, high angularity, and hardness (Moh's hardness of 5 to 6) of ACBFS. ACBFS aggregates have high polished stone values (PSV) tested according to AASHTO T279(11) and impart good frictional resistance to hot mix asphalt and surface treatments. (See references 6,7,8, and 12.)

Rutting Resistance: Asphalt concrete mixes containing ACBFS aggregates combine very high stabilities with good flow properties, resulting in a mix that resists rutting after cooling but is still compactable.

Stripping Resistance: Due to its hydrophobic nature, ACBFS has a high affinity for asphalt cement (rather than water), resulting in excellent adhesive bond between ACBFS aggregate particles and asphalt cement and excellent resistance to stripping.

DESIGN CONSIDERATIONS

Mix Design

Asphalt mixes containing blast furnace slag can be designed using standard laboratory procedures.

Structural Design

Conventional AASHTO pavement structural design methods are appropriate for asphalt pavements containing ACBFS.

CONSTRUCTION PROCEDURES

Material Handling and Storage

The same methods and equipment used to store or stockpile conventional aggregates are applicable to ACBFS. Due to its brittle nature, some care must be taken in handling ACBFS, since excessive handling could result in particle breakdown.

Mixing, Placing, and Compacting

Since ACBFS is more porous than conventional aggregates, longer retention time for drying at the hot mix plant may be required.

The same methods and equipment used for placing and compacting conventional pavements can be used for asphalt concrete containing ACBFS.

Quality Control

To minimize problems associated with the variable properties of some ACBFS aggregates, a comprehensive quality control testing program may be necessary to monitor the gradation, specific gravity, absorption, and angularity of ACBFS used in asphalt concrete.(2)

The same field testing procedures used for conventional hot mix asphalt mixes should be used for mixes containing blast furnace slag. Mixes should be sampled in accordance with AASHTO T168,(13) and tested for specific gravity in accordance with ASTM D2726(14) and in-place density in accordance with ASTM D2950.(15)

UNRESOLVED ISSUES

There is a need to evaluate factors that contribute to the lack of consistency in the physical properties (gradation, specific gravity, absorption, and angularity) of ACBFS aggregates among individual slag producers and its effect on performance problems such as flushing and ravelling in hot mix asphalt. In addition, formal quality control procedures should be instituted to monitor the quality of specific ACBFS sources to assist in mitigating these problems.

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INTRODUCTION

Ground granulated blast furnace slag (GGBFS) has been used for many years as a supplementary cementitious material in Portland cement concrete, either as a mineral admixture or as a component of blended cement. Using GGBFS as a partial Portland cement replacement takes advantage of the energy invested in the slag making process and its corresponding benefits with respect to the enhanced cementitious properties of the slag. Grinding slag for cement replacement requires only about 25 percent of the energy needed to manufacture Portland cement.(1)

The use of GGBFS in Portland cement is governed by AASHTO M302.(2) Three types of ground granulated slag cements are typically manufactured. They include Portland cement as covered by AASHTO M85(3), Portland blast furnace slag cement (blended cement Type IS), and slag cement (slag cement Type S) as per AASHTO M240.(4)

PERFORMANCE RECORD

Four state agencies are reported to be investigating the use of GGBFS as a supplementary cementitious material (Florida, Maryland, New Hampshire, and Oregon).(5) At least 11 states (Delaware, Florida, Indiana, Maryland, Massachusetts, Michigan, New Hampshire, North Carolina (limited use on experimental basis), Pennsylvania, South Carolina and Virginia) currently have specifications covering the use of GGBFS as a partial replacement for Portland cement. Some agencies have reported durability problems (salt scaling resistance) with exposed concrete containing blast furnace slag where the amount of slag cement exceeds about 25 percent of the total cement.(6)

The Environmental Protection Agency (EPA) has recommended that effective May 1, 1995, procuring agencies specifically include provision in all construction contracts for the use of GBBFS, as appropriate.(7)

MATERIAL PROCESSING REQUIREMENTS

Dewatering

Moisture in blast furnace slag, which occurs in the granulation process or in pelletized slag, should be removed by drying prior to the use of GGBFS as either an additive to Portland cement or a mineral admixture to Portland cement concrete.

Grinding

Processing for use as a supplementary cementitious material requires grinding of the slag, typically using the same or similar plant and equipment as for Portland cement production.

ENGINEERING PROPERTIES

Some of the engineering properties of GGBFS that are of particular interest when blast furnace slag is used as a supplementary cementitious material in Portland cement concrete include the hydraulic reactivity of the slag and its fineness.

Hydraulic Reactivity: Depending on the quenching process, the structure of pelletized blast furnace slag can range from crystalline (slow quench) to vitreous (rapid quench). Rapid quenching is important if cementitious properties are to be achieved. The chemical composition of GGBFS used in Portland cement concrete must also conform to sulfur and sulfate content limitations outlined in AASHTO M302.(1)

Fineness: Granulated blast furnace slag is a glassy granular material, and its particle distribution, shape, and grain size vary, depending on the chemical composition and method of production, from popcornlike friable particles to dense, sand-size grains. Pelletized blast furnace slag, in contrast to air-cooled and expanded blast furnace slag, has a relatively smooth texture and rounded shape. Grinding reduces the particle size to a cement fineness for use as a hydraulic cement, which is typically less than 3500 cm^2/g.(8)

Some of the properties of concrete mixes containing GGBFS that are of particular interest when it is used as partial cement replacement include strength development, workability, heat of hydration, resistance to alkali-aggregate reactivity, resistance to sulfate attack, and salt scaling.

Strength Development: Concrete containing GGBFS develops strength at a somewhat slower rate than concrete containing only Portland cement, but ultimately can develop equivalent strength. This can be a concern where early strength development is important (staged construction where the first structure must develop strength before the second structure can be placed). Low temperatures (cold weather) generally have a more adverse impact on strength development with concrete containing GGBFS than concrete containing only Portland cement.

Workability: Concrete containing GGBFS as a partial cement replacement has longer-lasting workability and low slump loss during hot weather construction.

Heat of Hydration: Concrete containing GGBFS exhibits a lower heat of hydration than conventional Portland cement concrete.

Alkali-Aggregate Reactivity: The use of GGBFS as a partial replacement for Portland cement can reduce available alkalis and can reduce the reaction between certain siliceous components of concrete aggregates and the alkalis in the concrete.(9)

Sulfate Resistance: Use of GGBFS as a partial cement replacement gives concrete moderate resistance to sulfate attack.(10)

Salt Scaling: Concrete containing high concentrations of GGBFS may be susceptible to salt scaling (the loss of surface layers of cement mortar during repeated freeze-thaw cycles). Due to this problem, some agencies limit the amount of slag in a Portland cement concrete mix to 25 percent of the total cement weight.(6)

DESIGN CONSIDERATIONS

Mix Design

The most frequently used proportioning recommendations for GGBFS use in concrete mix designs are covered in ACI 226.1R.(11) Some agencies require that a salt scaling test also be completed for selected concrete mixes subjected to deicing salts.(6,12)

Structural Design

Conventional AASHTO pavement structural design methods are appropriate for concrete mixes containing GGBFS.

CONSTRUCTION PROCEDURES

Material Handling and Storage

GGBFS (or cement containing GGBFS) is handled and stored like conventional Portland cement.

Mixing, Placing, and Compacting

The same equipment and procedures used for conventional Portland cement concrete may be used to batch, mix, transport, place, and finish concrete containing GGBFS.

Curing

The slower strength development of concrete containing GGBFS may require that the moisture be retained in the concrete for a longer period of time than what is normally required for conventional concrete. Scheduling of pavement construction should allow adequate time for the specified strength gain prior to the placement of traffic loads, the onset of freeze-thaw cycles, and the application of deicing salts.

Quality Control

The same quality control procedures used for conventional Portland cement concrete can be used for concrete containing GGBFS.

UNRESOLVED ISSUES

The primary issue associated with the use of slag cement is the reported loss of durability (salt scaling resistance) for exposed Portland cement concrete containing more than about 25 percent slag cement. It is unknown if any U.S. agencies are conducting specific research into this concern (some research has been reported in Canada).(5) During the mix design stage, a salt scaling resistance test (ASTM C672)(12) should be undertaken to assess the potential durability problems that may be encountered with the levels of GGBFS being used .

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INTRODUCTION

Air-cooled blast furnace slag (ACBFS) is considered by many specifying agencies to be a conventional aggregate that can be used in granular base applications. The high stability of ACBFS aggregates can be especially useful in construction over soft ground. Its ability to "lock up" in granular base applications provides good load transfer when placed on weaker subgrade. The lower compacted unit weight of blast furnace slag aggregates relative to conventional aggregates results in a higher yield (greater volume for the same weight).

PERFORMANCE RECORD

ACBFS has been successfully used as granular base or subbase material in many parts of the United States. At least seven states (California, Illinois, Indiana, Michigan, New Jersey, New York, and Pennsylvania) include ACBFS in their conventional granular base or subbase specifications.(1)

Some of the more desirable features of ACBFS in granular base applications include its ability to stabilize wet, soft underlying soils at early construction stages, good durability, ability to be placed in almost any weather, extremely high stability, and almost complete absence of settlement after compaction. Additionally, the high insulating value of blast furnace slag granular bases can be used to minimize frost heaving.

When ACBFS granular base is placed in poor drainage conditions, or other situations where it may be in extended contact with stagnant or slow moving water, sulfurous, discolored leachate may result. This leachate can result in sulfur-related odors and typically exhibits a yellow/green tinge, resulting from the presence of free sulfur and sulfur dioxide and a high pH.(2)

MATERIAL PROCESSING REQUIREMENTS

Crushing and Screening

ACBFS is readily processed using conventional crushing and screening equipment. The highest stabilities are obtained using crushed material with the largest maximum size that can be handled without segregation (generally 19 mm (3/4 in) to 38 mm (1-1/2 in)).

Quality Control

Leachate from the ACBFS aggregate should be checked by the processors to verify that it is not prone to discoloration and/or odor. Although aging delays the discoloration and sulfurous odor problems from ACBFS in contact with water, it does not eliminate them.(3) Recommended guidelines to minimize the likelihood of sulfurous leachate from ACBFS granular base are outlined below:

- ACBFS aggregates should be stockpiled for at least 1 month prior to shipping to the project.
- The ACBFS aggregates should pass the State of Illinois Testing and Acceptance Procedure of Crushed Slag Samples for Leachate Determination(4) (Bucket Test) prior to shipping to the project. (This test method has also been adopted by Ohio EPA.)
- ACBFS aggregates should only be used above grade as granular base in the pavement structure and must be adequately separated from water courses to prevent immersion, and should not be used in poorly drained areas or in contact with stagnant or slow moving water.

ENGINEERING PROPERTIES

Some of the engineering properties of ACBFS aggregates that are of particular interest when ACBFS is used in granular base applications include gradation, compacted density, friction angle, bearing capacity, freeze-thaw resistance, weathering, hardness and impact resistance, abrasion, and drainage characteristics.

Gradation: Blast furnace slag should be crushed and screened to produce a material that satisfies the grading requirements of granular base and subbase specifications, such as AASHTO M147.(5)

Compacted Density: The compacted density varies with size and grading of the slag, method of measuring, and bulk specific gravity of the slag. The compacted density of ACBFS ranges from 1120 kg/m^3 (70 lb/ft^3) to 1940 kg/m^3 (120 lb/ft^3), which is somewhat lower than that of conventional granular materials. Allowance for this differential should be considered during design and in specifications in order to ensure equal volume irrespective of the type of aggregate used.

Stability: ACBFS angularity and high friction angle (40° to 45°) contribute to high bearing capacity (California Bearing Ratio (CBR) greater than 100).

Freeze-Thaw Resistance: ACBFS aggregates display good durability with resistance to freeze-thaw weathering and erosion.

Hardness and Impact Resistance: The hardness of slag as measured by Moh's scale is between 5 and 6, corresponding to durable igneous rock.(6) However, ACBFS is quite brittle and prone to breakdown when subjected to impact loading.(7)

Abrasion: AASHTO M147(5) requirements for Los Angeles Abrasion loss for granular base aggregates are typically waived for ACBFS since no correlation between the Los Angeles Abrasion test loss for slag in laboratory tests and degradation in field applications has reportedly been observed. For this reason ASTM has deleted this test for slag in its specifications (e.g., ASTM D692, ASTM D1139), and major slag-using states, such as Michigan, Ohio and Indiana, do not use this test procedure with ACBFS.

Drainage Characteristics. ACBFS granular base is free draining and is not frost susceptible.(8)

DESIGN CONSIDERATIONS

The use of ACBFS aggregates in granular base applications is covered by conventional aggregate specifications in many jurisdictions. ACBFS aggregate can normally meet the requirements of AASHTO M147.(5)

Structural design procedures for granular base containing blast furnace slag are the same as design procedures for conventional granular materials.

CONSTRUCTION PROCEDURES

Material Handling and Storage

The same equipment and procedures used for conventional aggregate may be used to stockpile and handle conventional aggregates as appropriate for ACBFS. However, greater care is required when handling and stockpiling blast furnace slag aggregates to avoid brittle fracture that can result in excessive fines generation.

Placing and Compacting

Procedures should be employed to ensure uniform gradation and layer thickness. Good uniformity is obtained by combining the coarse and fine aggregates with optimum water for compaction at the blending plant just prior to placing. The material should be graded and placed in a manner that allows free drainage and prevents ponding within or adjacent to the material.

Quality Control

The same test procedures used for conventional aggregate are appropriate for ACBFS. Standard field and laboratory tests for compacted density and field measurement of compaction are given by AASHTO T191,(9) T205,(10) T238,(11) and T239(12) test methods.

UNRESOLVED ISSUES

There is a need to resolve the aesthetic and environmental concerns regarding the odor and discoloration of water due to ACBFS leachate by conducting research to determine the properties (e.g., pH, redox conditions, etc.) that result in the discoloration and odor encountered in the field.

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INTRODUCTION

Both air-cooled blast furnace slag (ACBFS) and expanded blast furnace slag can be used as a conventional aggregate in embankment or fill. They are generally considered by many specifying agencies to be conventional aggregates and require minimal processing to satisfy conventional soil and aggregate engineering requirements.(1,2,3)

PERFORMANCE RECORD

At least seven states have reported the use of blast furnace slag in embankment construction. They include Indiana, Kentucky, Maryland, Michigan, Missouri, New York, and Ohio.(4)

Some positive features of ACBFS and expanded blast furnace slag include their low compacted density (which results in reduced dead weight load, reduced lateral pressures, and favorable transportation costs on a volumetric basis), high stability and friction angle, ability to stabilize wet, soft underlying soils at early construction stages, and the almost complete absence of settlement after compaction. Expanded blast furnace slag can also provide some structural strength because of its cementitious properties.

Leaching of sulfurous compounds from ACBFS has been reported. (See references 5,6,7,8,9, and 10.) Investigation and testing have shown that when ACBFS is placed in poor drainage conditions and is in extended contact with stagnant or slow moving water, the contact water can exhibit a high pH, aesthetically undesirable odors (sulfur-related), and yellow/green color.(7,11)

MATERIAL PROCESSING REQUIREMENTS

Crushing

Blast furnace slag requires minimal processing to satisfy the physical requirements for use in embankments. Primary crushing is generally adequate to satisfy gradation requirements.

Quality Control

Leachate from the material should be checked to verify that it is not prone to discoloration. While aging delays the discoloration and sulfurous odor from ACBFS in contact with water, it does not completely eliminate this occurrence.(12)

The following are recommended guidelines to minimize the likelihood of sulfurous leachate from ACBFS:

- ACBFS aggregates should be stockpiled for at least 1 month prior to shipping to the project.
- The aged ACBFS should pass the State of Illinois Testing and Acceptance Procedure of Crushed Slag Samples for Leachate Determination (Bucket Test)(13) prior to shipping to the project.
- Aged ACBFS aggregates should only be used above the water table, and should be adequately separated from water courses to prevent submersion in water, and should not be used in poorly drained areas or in contact with stagnant or slow moving water.
- A good groundwater drainage system is recommended when ACBFS aggregate is used to allow free drainage and to prevent ponding within or against the ACBFS.

ENGINEERING PROPERTIES

Some of the engineering properties of ACBFS that are of particular interest when ACBFS is used in embankment or fill applications include gradation, stability, compacted density, drainage characteristics, and corrosivity.

Gradation: The gradation and physical requirements of AASHTO M145-82(14) are readily satisfied by ACBFS.

Stability: Due to its coarse texture and angular shape, ACBFS aggregate has a high friction angle (40° to 45°), has high bearing capacity (California Bearing Ratio (CBR) greater than 100), and demonstrates almost complete lack of postcompaction settlement.(15)

Compacted Density: The compacted density of ACBFS aggregates, which is in the range of 1120 kg/m^3 (70 lb/ft^3) to 1940 kg/m^3 (120 lb/ft^3), is usually lower than that of conventional embankment or fill materials (earth and rock). The bulk relative density of expanded slag is difficult to determine accurately, but its loose unit weight is about 70 percent of that of ACBFS. Typical unit weights for expanded blast furnace slag fine aggregates are 800 kg/m^3 (50 lb/ft^3) to 1040 kg/m^3 (65 lb/ft^3) and from 560 kg/m^3 (35 lb/ft^3) to 800 kg/m^3 (50 lb/ft^3) for coarse aggregates.(16)

Drainage Characteristics: ACBFS and expanded blast furnace slag are nonplastic and free draining and are not frost susceptible.

Corrosivity: Blast furnace slag is mildly alkaline, with a pH in nonstagnant water mixtures in the range of 8 to 10. Despite the fact that blast furnace slag contains a small component of elemental sulfur (1 to 2 percent), the leachate is slightly alkaline and does not present a corrosion risk to steel (e.g., steel pilings).(17,18)

DESIGN CONSIDERATIONS

There are no standard specifications covering blast furnace slag use as embankment or fill material. The supplier may be required to satisfy moisture content criteria according to AASHTO T99.(19)

Design procedures for embankments or fill containing blast furnace slag are the same as design procedures for embankments or fills using conventional materials.

CONSTRUCTION PROCEDURES

Material Handling and Storage

The same equipment and procedures used for handling and stockpiling conventional aggregates may be used to handle and stockpile ACBFS.

Placing and Compacting

ACBFS should be placed in a manner that allows free drainage and prevents ponding within or against the material. The same methods and equipment used to place and compact conventional aggregate can be used to place and compact blast furnace slag.

The same test procedures used for conventional aggregate are appropriate for ACBFS. Standard field and laboratory tests for compacted density and field measurement of compaction are given by AASHTO T191,(20) T205,(21) T238,(22) and T239(23) test methods.

UNRESOLVED ISSUES

There is a need to resolve the aesthetic environmental concerns regarding the odor and discoloration of water because of ACBFS leachate by conducting research to determine the properties (e.g., pH, redox conditions, etc.) that result in the odor and discoloration encountered in the field.

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COAL BOTTOM ASH/ BOILER SLAG

ORIGIN

Coal bottom ash and boiler slag are the coarse, granular, incombustible by-products that are collected from the bottom of furnaces that burn coal for the generation of steam, the production of electric power, or both. The majority of these coal by-products are produced at coal-fired electric utility generating stations, although considerable bottom ash and/or boiler slag are also produced from many smaller industrial or institutional coal-fired boilers and from coal-burning independent power production facilities. The type of by-product (i.e., bottom ash or boiler slag) produced depends on the type of furnace used to burn the coal.

Bottom Ash

The most common type of coal-burning furnace in the electric utility industry is the dry-bottom pulverized coal boiler. When pulverized coal is burned in a dry-bottom boiler, about 80 percent of the unburned material or ash is entrained in the flue gas and is captured and recovered as fly ash. The remaining 20 percent of the ash is dry bottom ash, a dark gray, granular, porous, predominantly sand size minus 12.7mm (½ in) material that is collected in a water-filled hopper at the bottom of the furnace.(1) When a sufficient amount of bottom ash drops into the hopper, it is removed by means of high-pressure water jets and conveyed by sluiceways either to a disposal pond or to a decant basin for dewatering, crushing, and stockpiling for disposal or use.(2) During 1996, the utility industry generated 14.5 million metric tons (16.1 million tons) of bottom ash.(3)

Boiler Slag

There are two types of wet-bottom boilers: the slag-tap boiler and the cyclone boiler. The slag-tap boiler burns pulverized coal and the cyclone boiler burns crushed coal. In each type, the bottom ash is kept in a molten state and tapped off as a liquid. Both boiler types have a solid base with an orifice that can be opened to permit the molten ash that has collected at the base to flow into the ash hopper below. The ash hopper in wet-bottom furnaces contains quenching water. When the molten slag comes in contact with the quenching water, it fractures instantly, crystallizes, and forms pellets. The resulting boiler slag, often referred to as "black beauty," is a coarse, hard, black, angular, glassy material.

When pulverized coal is burned in a slag-tap furnace, as much as 50 percent of the ash is retained in the furnace as boiler slag. In a cyclone furnace, which burns crushed coal, some 70 to 80 percent of the ash is retained as boiler slag, with only 20 to 30 percent leaving the furnace in the form of fly ash.(1)

Wet-bottom boiler slag is a term that describes the molten condition of the ash as it is drawn from the bottom of the slag-tap or cyclone furnaces. At intervals, high-pressure water jets wash the boiler slag from the hopper pit into a sluiceway which then conveys it to a collection basin for dewatering, possible crushing or screening, and either disposal or reuse.(4) During 1995, the utility industry in the United States generated 2.3 million metric tons (2.6 million tons) of boiler slag.(3)

A general diagram depicting the production and processing operations associated with bottom ash and boiler slag management is presented in Figure 4-1.

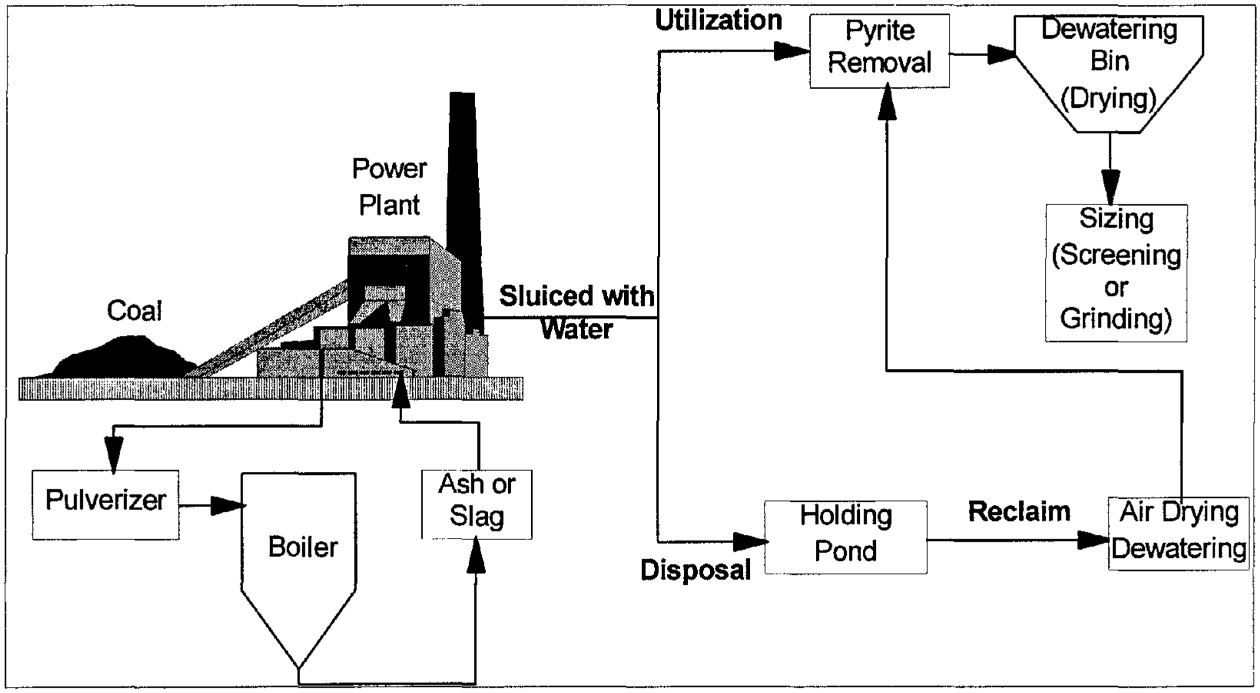

Figure 4-1. Production and processing of bottom ash or boiler slag.

Additional information on the use of bottom ash and/or boiler slag can be obtained from:

American Coal Ash Association (ACAA)
2760 Eisenhower Avenue, Suite 304
Alexandria, Virginia 22314

Electric Power Research Institute
3412 Hillview Road
Palo Alto, California 94304

CURRENT MANAGEMENT OPTIONS

Recycling

According to recent statistics on coal combustion by-product utilization, 30.3 percent of all bottom ash and 93.3 percent of all boiler slag produced in 1996 were utilized. Leading bottom ash applications are snow and ice control, aggregate in lightweight concrete masonry units, and raw feed material for production of Portland cement. Bottom ash has also been used as road base and subbase aggregate, structural fill material,(5) and fine aggregate in asphalt paving and flowable fill. Leading boiler slag applications are blasting grit, roofing shingle granules, and snow and ice control. Boiler slag has also been used as aggregate in asphalt paving, structural fill,(5) and road base and subbase applications.(2)

The U. S. EPA is presently undertaking a study of power plant wastes prior to disposal by the utility. It is possible that the EPA study on mixed power plant wastes could have a regulatory impact on beneficial use or reuse of any mixed materials. It is anticipated that this investigation will be completed in 1998.

Disposal

Discarded bottom ash and boiler slag are either landfilled or sluiced to storage lagoons. When sluiced to storage lagoons, the bottom ash or boiler slag is usually combined with fly ash. This blend of fly ash and bottom ash or boiler slag is referred to as ponded ash. Approximately 30 percent of all coal ash is handled wet and disposed of as ponded ash.(3)

Ponded ash is potentially useable, but variable in its characteristics because of its manner of disposal. Because of differences in the unit weight of fly ash and bottom ash or boiler slag, the coarser bottom ash or boiler slag particles settle first and the finer fly ash remains in suspension longer.

Ponded ash can be reclaimed and stockpiled, during which time it can be dewatered. Under favorable drying conditions, ponded ash may be dewatered into a range of moisture that will be within the vicinity of its optimum moisture content. The higher the percentage of bottom ash or boiler slag there is in ponded ash, the easier it is to dewater and the greater its potential for reuse. Reclaimed ponded ash has been used in stabilized base or subbase mixes and in embankment construction, and can also be used as fine aggregate or filler material in flowable fill.

MARKET SOURCES

Although electric utility companies produce ash at their coal-fired power plants, most utilities do not handle, dispose of, or sell the ash that they produce. For the most part, management of bottom ash or boiler slag is contracted out to ash marketing firms or to local hauling contractors. There are approximately 50 commercial ash marketing firms operating throughout the United States, in all states except Hawaii. In addition to commercial ash marketing organizations, certain coal-burning electric utility companies have a formal ash marketing program of their own. Most coal-burning electric utility companies currently employ an ash marketing specialist, who is responsible for monitoring ash generation, quality, use or disposal, and for interfacing with the ash marketers or brokers who are under contract to the utility companies.

HIGHWAY USES AND PROCESSING REQUIREMENTS

Asphalt Concrete Aggregate (Bottom Ash and Boiler Slag)

Both bottom ash and boiler slag have been used as fine aggregate substitute in hot mix asphalt wearing surfaces and base courses, and emulsified asphalt cold mix wearing surfaces and base courses. Because of the "popcorn," clinkerlike low durability nature of some bottom ash particles, bottom ash has been used more frequently in base courses than in wearing surfaces. Boiler slag has been used in wearing surfaces, base courses and asphalt surface treatment or seal coat applications. There are no known uses of bottom ash in asphalt surface treatment or seal coat applications.

Screening of oversized particles and blending with other aggregates will typically be required to use bottom ash and boiler slag in paving applications. Pyrites that may be present in the bottom ash should also be removed (with electromagnets) prior to use. Pyrites (iron sulfide) are volumetrically unstable, expansive, and produce a reddish stain when exposed to water over an extended time period.

Granular Base (Bottom Ash and Boiler Slag)

Both bottom ash and boiler slag have occasionally been used as unbound aggregate or granular base material for pavement construction. Bottom ash and boiler slag are considered fine aggregates in this use. To meet required specifications, the bottom ash or slag may need to be blended with other natural aggregates prior to its use as a base or subbase material. Screening or grinding may also be necessary prior to use, particularly for the bottom ash, where large particle sizes, typically greater than 19 mm (3/4 in), are present in the ash.

Stabilized Base Aggregate (Bottom Ash and Boiler Slag)

Bottom ash and boiler slag have been used in stabilized base applications. Stabilized base or subbase mixtures contain a blend of an aggregate and cementitious materials that bind the aggregates, providing the mixture with greater bearing strength. Types of cementitious materials typically used include Portland cement, cement kiln dust, or pozzolans with activators, such as lime, cement kiln dusts, and lime kiln dusts. When constructing a stabilized base using either bottom ash or boiler slag, both moisture control and proper sizing are required. Deleterious materials such as pyrites should also be removed.

Embankment or Backfill Material (Mainly Bottom Ash)

Bottom ash and ponded ash have been used as structural fill materials for the construction of highway embankments and/or the backfilling of abutments, retaining walls, or trenches. These materials may also be used as pipe bedding in lieu of sand or pea gravel. To be suitable for these applications, the bottom ash or ponded ash must be at or reasonably close to its optimum moisture content, free of pyrites and/or "popcorn" particles, and must be non-corrosive. Reclaimed ponded ash must be stockpiled and adequately dewatered prior to use. Bottom ash may require screening or grinding to remove or reduce oversize materials (greater than 19 mm (3/4 in) in size.

Flowable Fill Aggregate (Mainly Bottom Ash)

Bottom ash has been used as an aggregate material in flowable fill mixes. Ponded ash also has the potential for being reclaimed and used in flowable fill. Since most flowable fill mixes require comparatively low compressive strength (to allow for excavation at a later time, if necessary), no advance processing of bottom ash or ponded ash is needed. Neither bottom ash nor ponded ash needs to be at any particular moisture content to be used in flowable fill mixes because the amount of water in the mix can be adjusted in order to provide the desired flowability.

MATERIAL PROPERTIES

Physical Properties

Bottom ashes have angular particles with a very porous surface texture. Bottom ash particles range in size from a fine gravel to a fine sand with very low percentages of silt-clay sized particles. The ash is usually a well-graded material, although variations in particle size distribution may be encountered in ash samples taken from the same power plant at different times. Bottom ash is predominantly sand-sized, usually with 50 to 90 percent passing a 4.75 mm (No. 4) sieve, 10 to 60 percent passing a 0.42 mm (No. 40) sieve, 0 to 10 percent passing a 0.075 mm (No. 200) sieve, and a top size usually ranging from 19 mm (3/4 in) to 38.1 mm (1-1/2 in). Table 4-1 compares the typical gradations of bottom ash and boiler slag.

Table 4-1. Particle size distribution of bottom ash and boiler slag.(4)
(percent by weight passing)

	Bottom Ash			**Boiler Slag**		
Sieve Size	**Glasgow, WV**	**New Haven, WV**	**Moundsville, WV**	**Willow Island, WV**	**Rockdale, TX**	**Moundsville, WV**
38 mm (1-1/2 in)	100	99	100	100	100	100
19 mm (3/4 in)	100	95	100	100	100	100
9.5 mm (3/8 in)	100	87	73	99	100	97
4.75 mm (No. 4)	90	77	52	97	99	90
2.36 mm (No. 8)	80	57	32	85	88	62
1.18 mm (No. 16)	72	42	17	46	42	16
0.60 mm (No. 30)	65	29	10	23	10	4
0.30 mm (No. 50)	56	19	5	12	5	2
0.15 mm (No. 100)	35	15	2	6	2	1
0.075 mm (No. 200)	9	4	1	4	1	0.5

Boiler slags are predominantly single-sized and within a range of 5.0 to 0.5 mm (No. 4 to No. 40 sieve). Ordinarily, boiler slags have a smooth surface texture, but if gases are trapped in the slag as it is tapped from the furnace, the quenched slag will become somewhat vesicular or porous. Boiler slag from the burning of lignite or subbituminous coal tends to be more porous than that of the eastern bituminous coals.(6) Boiler slag is essentially a coarse to medium sand with 90 to 100 percent passing a 4.75 mm (No. 4) sieve, 40 to 60 percent passing a 2.0 mm (No. 10) sieve, 10 percent or less passing a 0.42 mm (No. 40) sieve, and 5 percent or less passing a 0.075 mm (No. 200) sieve.(4)

The specific gravity of the dry bottom ash is a function of chemical composition, with higher carbon content resulting in lower specific gravity. Bottom ash with a low specific gravity has a porous or vesicular texture, a characteristic of "popcorn" particles that readily degrade under loading or compaction.(7) Table 4-2 lists some typical physical properties of bottom ash and boiler slags.

Table 4-2. Typical physical properties of bottom ash and boiler slag.

Property	Bottom Ash	Boiler Slag
Specific Gravity(6)	2.1 - 2.7	2.3 - 2.9
Dry Unit Weight(6)	720 - 1600 kg/m^3 (45 - 100 lb/ft^3)	960 - 1440 kg/m^3 (60 - 90 lb/ft^3)
Plasticity(6)	None	None
Absorption(4)	0.8 - 2.0%	0.3 - 1.1%

Chemical Properties

Bottom ash and boiler slag are composed principally of silica, alumina, and iron, with smaller percentages of calcium, magnesium, sulfates, and other compounds. The composition of the bottom ash or boiler slag particles is controlled primarily by the source of the coal and not by the type of furnace. Table 4-3 presents a chemical analysis of selected samples of bottom ash and boiler slag from different coal types and different regions.

Table 4-3. Chemical composition of selected bottom ash and boiler slag samples (percent by weight).(4)

Ash Type:	**Bottom Ash**					**Boiler Slag**		
Coal Type:	**Bituminous**			**Sub-bituminous**	**Lignite**	**Bituminous**		**Lignite**
Location:	**West Virginia**		**Ohio**	**Texas**		**West Virginia**		**North Dakota**
SiO_2	53.6	45.9	47.1	45.4	70.0	48.9	53.6	40.5
Al_2O_3	28.3	25.1	28.3	19.3	15.9	21.9	22.7	13.8
Fe_sO_3	5.8	14.3	10.7	9.7	2.0	14.3	10.3	14.2
CaO	0.4	1.4	0.4	15.3	6.0	1.4	1.4	22.4
MgO	4.2	5.2	5.2	3.1	1.9	5.2	5.2	5.6
Na_2O	1.0	0.7	0.8	1.0	0.6	0.7	1.2	1.7
K_2O	0.3	0.2	0.2	-	0.1	0.1	0.1	1.1

Bottom ash or boiler slag derived from lignite or sub-bituminous coals has a higher percentage of calcium than the bottom ash or boiler slag from anthracite or bituminous coals. Although sulfate is not shown in Table 4-2, it is usually very low (less than 1.0 percent), unless pyrites have not been removed from the bottom ash or boiler slag.

Due to the salt content and, in some cases, the low pH of bottom ash and boiler slag, these materials could exhibit corrosive properties. When using bottom ash or boiler slag in an embankment, backfill, subbase, or even possibly in a base course, the potential for corrosion of metal structures that may come in contact with the material is of concern and should be investigated prior to use.

Corrosivity indicator tests normally used to evaluate bottom ash or boiler slag are pH, electrical resistivity, soluble chloride content, and soluble sulfate content. Materials are judged to be noncorrosive if the pH exceeds 5.5, the electrical resistivity is greater than 1,500 ohm-centimeters, the soluble chloride content is less than 200 parts per million (ppm), or the soluble sulfate content is less than 1,000 parts per million (ppm).(8)

Mechanical Properties

Table 4-4 lists some typical values for bottom ash and boiler slag compaction characteristics (maximum dry density and optimum moisture), durability characteristics (Los Angeles abrasion and sodium sulfate soundness), shear strength and bearing strength characteristics (friction angle and), and permeability.

The maximum dry density values of bottom ash and boiler slag are usually from 10 to 25 percent lower than those of naturally occurring granular materials. The optimum moisture content values of bottom ash and boiler slag are both higher than those of naturally occurring granular materials, with bottom ash having a considerably higher optimum moisture content than boiler slag.

Boiler slag usually exhibits less abrasion loss and soundness loss than bottom ash because of its glassy surface texture and lower porosity.(9) In some power plants, coal pyrites are disposed of with the bottom ash or boiler slag. In such cases, some pyrite or soluble sulfate is contained in the bottom ash or boiler slag,(9) which may be reflected in higher sodium sulfate soundness loss values.

Reported friction angle values are within the same range as those for sand and other conventional fine aggregate sources.(7)

Table 4-4. Typical mechanical properties of bottom ash and boiler slag.

Property	Bottom Ash	Boiler Slag
Maximum Dry Density kg/m^3 (lb/ft^3)$^{(7)}$	1210 - 1620 (75 - 100)	1330 - 1650 (82 - 102)
Optimum Moisture Content, %$^{(7)}$	Usually <20 12 - 24 range	8 - 20
Los Angeles Abrasion Loss %$^{(4)}$	30 - 50	24 - 48
Sodium Sulfate Soundness Loss %$^{(4)}$	1.5 - 10	1 - 9
Shear Strength (Friction Angle)$^{(6)}$	38 - 42° 32 - 45° (<9.5 mm size)	38 - 42° 36 - 46° (<9.5 mm size)
California Bearing Ratio (CBR) %$^{(6)}$	40 - 70	40 - 70
Permeability Coefficient cm/sec$^{(6)}$	10^{-2} - 10^{-3}	10^{-2} - 10^{-3}

California Bearing Ratio values are comparable to those of high-quality gravel base materials. Dry bottom ash and boiler slag can both be expected to have permeability coefficients that are within approximately the same range.(7) The permeability is related to the percent fines (minus 0.075 mm or No. 200 sieve) of the material.

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INTRODUCTION

Bottom ash and boiler slag can be used as aggregates in hot mix asphalt base courses or wearing surfaces, emulsified asphalt cold mix bases or surfaces, and asphalt surface treatments or seal coats.

Bottom ash, produced in dry-bottom boilers, is usually sufficiently well-graded that it does not need to be blended with other fine aggregates to meet gradation requirements. However, bottom ash particles are less durable than conventional aggregates. Consequently, bottom ash is better suited for use in base course and shoulder mixtures or in cold mix applications, as opposed to wearing surface mixtures. Most of the previous use of bottom ash has been in cold mix projects on low-volume secondary roadways.

Boiler slag is produced in wet-bottom boilers, is uniformly sized, and consists of hard, durable, glassy particles. Boiler slag has to be blended with other fine aggregates to meet gradation requirements, but has been used more frequently in asphalt paving than bottom ash. Boiler slag has been used mainly in hot mix wearing surfaces, where it has been found to enhance skid resistance, and, to a lesser extent, in surface treatment or seal coat applications.

PERFORMANCE RECORD

Bottom ash and boiler slag have been used with considerable success as fine aggregates in asphalt paving mixtures for at least the past 25 years in different sections of the United States. The American Coal Ash Association recently reported that during 1996 more than 75,000 metric tons (83,000 tons) of boiler slag and nearly 14,400 metric tons (16,000 tons) of bottom ash were used in asphalt paving.(1)

A 1994 survey of all 50 state transportation agencies indicated that five states have made some recent use of bottom ash and/or boiler slag as an aggregate in asphalt paving on state roadways. These five states are Arkansas, Missouri, Texas, West Virginia, and Wyoming.(2) Previous surveys have reported bottom ash and boiler slag usage in up to as many as 11 different states, although such usage includes some projects on nonstate roadways.(3)

Bottom Ash

Bottom ash is a somewhat variable material that may sometimes contain pyrites or lightweight, porous "popcorn" particles. As a result, it is not frequently used as an aggregate source in hot mix asphalt paving mixes, especially wearing surfaces. Bottom ash has been used more frequently in cold mix emulsified asphalt mixtures, hot mix base course mixtures, or in shoulder construction, where gradation requirements and durability considerations are not as critical as in hot mix wearing surface mixtures.(4)

The most extensive use of bottom ash in bituminous paving has been in West Virginia, where, during the 1970's and 1980's, bottom ash was cold mixed with 6 to 7 percent by weight of emulsified asphalt and used in the paving of secondary roads where traffic volumes are lower and durability concerns are reduced. In some cases, the bottom ash was also blended with boiler slag. Similar applications have also been made in eastern Ohio.(5)

Bottom ash has been used occasionally as an aggregate in hot mix asphalt, but usually only when blended with conventional aggregates. There have been periodic indications of problems with paving mixtures in West Virginia containing bottom ash, in which pyrite contamination in the bottom ash had not been considered. Pyrite particles will weather in service, despite being coated with asphalt cement, causing popouts and deep red stains in the pavement surface.(8) Bottom ash has also been used in hot mix asphalt in some western states.

Boiler Slag

Boiler slag has been used more frequently in hot mix asphalt than bottom ash because of its hard, durable particles and resistance to surface wear. Boiler slag has also been used in hot mix asphalt wearing surface mixtures because of its affinity for asphalt and its dust-free surface, which aids in asphalt adhesion and resistance to stripping.(6) Another of the properties of boiler slag that enhances its value as an aggregate in bituminous paving is its permanent black color, which is not affected by sun or weather. The black color also aids in the melting of snow from the road surface during the winter.(7)

Since boiler slag has a uniform particle sizing, it is commonly blended with other aggregates for use in asphalt mixtures. As a rule of thumb, paving mixture stability is likely to suffer if the percentage of boiler slag exceeds 50 percent.(8)

Boiler slag was first used in asphalt paving many years ago in Hammond, Indiana, where, on an experimental basis, it was blended with conventional aggregate to help solve the problem of aggregate polishing. The success of that and several other demonstration projects in Indiana led to its acceptance and use in that state and several others, including Ohio, Michigan, Missouri, and West Virginia. Boiler slag has also been used as an aggregate in hot mix asphalt paving in a number of cities such as Cincinnati and Columbus, Ohio, as well as in Tampa, Florida.(9)

In West Virginia, boiler slag has been blended with graded river sand for resurfacing applications, where thin overlays are used. Typical sections ranged in thickness from 12.7 to 50.8 mm (1/2 to 2 in) and were composed of 50 percent by weight boiler slag, 39 percent river sand, 3 percent fly ash, and 8 percent asphalt cement. Some of these sections were able to provide more than 10 years of service with little change in texture, despite being subjected to heavy truck traffic.(6)

Some 10,000 tons of boiler slag were used to construct the wearing surface and shoulders of a portion of Interstate Route 94 near the Detroit Airport. This section of roadway was placed during the late 1970's and reportedly performed well into the mid 1980's.(10)

Boiler slag from lignite coal was successfully used for street resurfacing work in parts of southern Texas for many years. The paving mixes consisted of a blend of 75 percent by weight of lignite boiler slag and 25 percent limestone screenings, with an asphalt content of 6 to 7 percent by weight of aggregate. These pavements have reportedly held up well with no signs of shoving or raveling, despite heavy truck traffic, while maintaining a dark, black texture, nonskid properties and smooth riding quality.(11)

The City of Sioux City, Iowa, has incorporated optimum amounts of boiler slag and fly ash mineral filler in an asphalt hot mix surface course called "Carpet Coat." The mix consists of 56 percent by weight boiler slag, 17 percent quartzite, 14 percent sand, 7 percent fly ash, and 6 percent asphalt cement.(12)

Boiler slag has also been used very successfully as a seal coat aggregate for bituminous surface treatments in a number of states, especially in municipal road construction projects. The boiler slag provided better coverage per mile than limestone chips and retained its rich black color, while the surface of the stone chip gradually acquired a faded, gray appearance. Significant cost savings using boiler slag in this application during the mid 1980's have been documented.(13)

The use of power plant aggregates in surface treatment or seal coat applications is believed to be confined almost exclusively to boiler slag. There are no known uses of bottom ash as a seal coat aggregate in asphalt surface treatments.

MATERIAL PROCESSING REQUIREMENTS

Cleaning

Pyrites present in the coal before burning should be removed during the pulverizing step and should not be allowed to be collected together with the bottom ash or boiler slag. If pyrites are present in the bottom ash or boiler slag, they should be removed by electromagnets, media separation, or other means.

Screening

Oversize or agglomerated "popcorn" particles may be present in some bottom ash sources and should be removed by screening or scalping the material over a 19 mm (3/4 in) or 12.7 mm (1/2 in) screen.

Blending

Boiler slag will almost always require blending with other aggregate sources to meet applicable gradation specifications. Bottom ash may require blending with other aggregates, although it is considerably more well-graded than boiler slag.

Drying

Since aggregates used to produce hot mix asphalt are dried before blending with asphalt cement, moisture that may be present in bottom ash can be removed. Excessive moisture in the aggregates, however, will reduce the production rate of the paving material. Both bottom ash and boiler slag are relatively easy to dewater, particularly boiler slag, which consists of glassy particles. Ponded ash, which is usually a mixture of fly ash and bottom ash or boiler slag, must be stockpiled and allowed to drain sufficiently prior to use, preferably to a surface dry condition.

When used in a cold mix application, the bottom ash should be at least surface dry so that moisture does not interfere with the coating of the ash particles by the emulsified asphalt. Boiler slag should also be in a surface dry condition when used as a seal coat aggregate.

ENGINEERING PROPERTIES

Both bottom ash and boiler slag are used as fine aggregates in asphalt paving applications. Properties of bottom ash and boiler slag that are of particular interest when they are used in asphalt concrete include gradation, specific gravity, absorption, and durability. Table 4-5 shows some of the engineering properties of bottom ash and boiler slag from power plants in West Virginia.(15)

Table 4-5. Engineering properties of selected bottom ashes and boiler slags

Power Plant Source	Boiler Type	Bulk Sp. Gravity	% Water Absorption	L.A. Abrasion	$MgSO_4$ Soundness	Friable Particles
Fort Martin	Dry bottom	2.31	2.0	40	6	Yes
Mitchell	Dry bottom	2.68	0.8	37	10	None
Hatfield	Dry bottom	2.39	1.7	39	–	Yes
Harrison	Dry bottom	2.66	1.0	38	–	Some
Kammer	Wet bottom	2.76	0.3	37	10	None
Willow Island	Wet bottom	2.72	0.3	33	15	None
Limestone Sand	–	2.65	1.1	–	–	–

Gradation: ASTM D1073 defines a fine aggregate in asphalt paving mixtures as an aggregate that passes the 9.5 mm (3/8 inch) sieve.(14) Boiler slag, with few exceptions, meets this size requirement and most bottom ash sources, with minimal screening of oversize material, will satisfy this definition of a fine aggregate. Bottom ash is predominantly sand-sized, usually with 50 to 90 percent passing a 4.75 mm (No. 4) sieve.

Specific Gravity and Absorption: Bottom ash generally has lower specific gravity and higher absorption values than limestone sand, while boiler slag is comparable in specific gravity with lower absorption than limestone sand.(15)

Durability: Bottom ash and boiler slag exhibit marginal durability as measured by the Los Angeles abrasion test, with bottom ash percent loss values between 30 and 50 and boiler slag somewhat lower. Most bottom ash samples have some friable particles, while boiler slag normally does not.

Soundness: Soundness values are generally found to be within ASTM D1073 weight loss specifications of not more than 15 percent after five cycles when sodium sulfate is used, or not more than 20 percent after five cycles when magnesium sulfate is used. Values for both boiler slag and bottom ash are generally found to be less than 10 percent.(15)

DESIGN CONSIDERATIONS

Mix Design

Bottom Ash

Dry bottom ash has received much less usage than boiler slag in asphalt paving and most of the experience in using bottom ash for this purpose has been in cold mixes. A serious consideration with some sources of dry bottom ash is the presence of friable "popcorn" particles, which can break down under compaction. For this reason, bottom ash is more appropriate for use in base course rather than surface mixtures.(16)

Because many bottom ashes contain friable "popcorn" particles that are also absorptive, the asphalt contents of hot mixes or cold mixes containing some percentage of bottom ash will be higher than those of mixes with conventional aggregates. Although the asphalt contents of mixes containing bottom ash will be greater than the asphalt contents of conventional asphalt paving mixes, the total amount of asphalt cement used should not be significantly greater because of the reduced unit weight of the mixes containing bottom ash. Bottom ash mixes are also likely to have relatively high air void contents. The high air voids are attributable to the high angle of internal friction and the rough surface texture of the bottom ash particles.(16)

Because of comparatively high optimum asphalt contents of mixtures using bottom ash as the only aggregate, combining bottom ash with conventional aggregates is recommended. Increased percentages of conventional aggregate result in a reduction in the optimum asphalt content. The primary benefit to be realized from blending with conventional aggregates is an improvement in the durability of the paving mix.

The addition of bottom ash can alter Marshall stability values, and stability must be examined in each mix design. Immersion-compression testing(17) indicates that moisture damage potential does not appear to be critical in paving mixtures containing bottom ash.(18) However, this test is too short in duration to detect particle degradation due to pyrites in the bottom ash.(16) It has been reported that kneading compaction(19) more closely approximates field compaction conditions than Marshall drop hammer compaction.(18)

Boiler Slag

The uniform gradation and smooth surface texture commonly associated with most boiler slags require that these materials be blended with other aggregates for use in asphalt paving mixtures. The blend proportions of boiler slag and conventional aggregate(s) will be dictated mainly by the size distribution of the materials and the requirements of the gradation specifications. Percentages of boiler slag ranging from 40 to 50 percent by weight of the total mix have been successfully used on a number of past projects. The best use of boiler slag is as a partial replacement for the sand fraction of hot mix base and surface course mixtures. The type of aggregate used and the relative proportions of the boiler slag and aggregate have a significant influence on the properties of the paving mixture.(8)

Marshall stability and flow values have been found to decrease as the percentage of boiler slag is increased for a given compactive effort. Mixes blended with rounded siliceous aggregates, such as uncrushed river sand, result in lower quality mixtures than blends containing crushed stone, which possess more desirable angularity and surface texture. Blending crushed stone aggregates with boiler slag is recommended because most boiler slags lack microtexture, which increases the ability of aggregate to retain its asphalt coating and to provide skid resistance.(15)

Optimum skid resistance using boiler slag is best found in open-graded sand mixes using boiler slag as the top-sized aggregate. However, such mixes should limit the percentage of boiler slag in the mix and avoid low filler content. Rounded river sands should also be avoided. Boiler slag does not appear to be as helpful in terms of skid resistance in coarse-graded mixtures, especially if the coarse aggregate is polish susceptible.(8)

The effect of compaction method on mixture properties is quite pronounced with blends of boiler slag and sand. Kneading compaction improves the stability and flow of such mixes, compared with Marshall drop hammer compaction. Obtaining adequate compaction is essential with boiler slag mixtures. The best mixtures are produced by blending boiler slag with well-graded, angular, rough-textured aggregate and limiting the percentage of boiler slag to 50 percent or less.(17)

It is possible that some of the more vesicular (porous) boiler slag sources could be used in greater percentages, but excessively vesicular slags tend to be weak and lack crushing resistance.(16)

These types of boiler slag may also be more absorptive than typical boiler slag sources and require a higher percentage of asphalt cement.

Boiler slag asphalt mixtures have performed well with respect to their retention of stability in the presence of water. When evaluated using the Marshall immersion-compression test,(17) boiler slag mixtures yielded acceptable stability retention values.(8)

Structural Design

Conventional AASHTO pavement structural design methods are appropriate for asphalt pavements incorporating bottom ash/boiler slag in the mix.(20)

Similarly, pavement thickness design procedures for cold mix overlays containing bottom ash or boiler slag, or a blend of the two, should not be any different from the thickness design procedures normally used for cold mix overlays using conventional aggregates. Modified structural numbers (SN) for cold mix overlays containing bottom ash and/or boiler slag should be the same as those normally used by the local jurisdiction for conventional cold mix overlays.

CONSTRUCTION PROCEDURES

Bottom Ash

Material Handling and Storage

Bottom ash can be handled and stored or stockpiled using the same methods and equipment that are normally used for handling and storage of conventional aggregates. However, as noted previously, prospective users of bottom ash must be aware of the possible presence of pyrites in the bottom ash and, if such pyrites were not removed prior to burning the coal, they must be removed from the bottom ash prior to its use in asphalt paving.

Mixing, Placing, and Compacting

The same methods and equipment used for mixing, placing, and compacting conventional pavements are applicable to asphalt pavements containing bottom ash.

When bottom ash is used in hot mix applications, it usually must be blended with other aggregates. However, dry bottom ash used in cold mix applications may not have to be blended with other aggregate. Such mixes can be prepared cold by mixing with emulsified asphalt at a central pugmill mixing plant and can usually be stockpiled for 10 days or more.

Cold mixes containing bottom ash can be placed with a paver or a spreader box, or, in some cases, can even be dumped and leveled with a grader. Adequate compaction is usually achieved from three to four passes with a pneumatic roller, followed by one or two passes from a steel-wheeled roller.(15)

Laydown characteristics of dry bottom ash cold mixes have been found to be excellent with the use of either a spreader box or a conventional paving machine. Lifts of up to 200 mm (8 in) loose were attempted in a spreader box with good results. It is believed that lifts greater than 200 mm (8 in) in loose thickness would probably be difficult to compact.(15)

Boiler Slag

Material Handling and Storage

Boiler slag can be handled and stored or stockpiled using the same methods and equipment that are normally used for handling and storage of conventional aggregates.

Mixing, Placing and Compacting

The same methods and equipment used for mixing, placing and compacting conventional pavements are applicable to asphalt pavements containing boiler slag.

Mixtures with acceptable skid resistance that use boiler slag as the top size aggregate can be designed by limiting the percentage of boiler slag in the mix and by avoiding open-graded mixtures with low filler content.(18)

UNRESOLVED ISSUES

Some, but not all, bottom ash sources may contain pyrite particles and/or soluble iron sulfate particles. These particles, if not separated and removed prior to mixing with asphalt, will eventually weather in the pavement, producing popouts and causing unsightly staining. These particles are usually associated with low pH values, which are indicative of the presence of excessive sulfate. A more direct test method is needed to identify these undesirable particles, particularly the pyrites, so they can be removed from the bottom ash before being incorporated into a paving mix.

Bottom ash may also contain friable, porous "popcorn" particles. If so, such bottom ashes should not be used in asphalt surface mixes unless they are precrushed before being mixed with asphalt. The performance of wearing surface mixes with precrushed bottom ash aggregate should be evaluated in comparison with more conventional asphalt paving mixes.

Some standard test methods are not appropriate for evaluating bottom ash and boiler slag and can result in the rejection of otherwise acceptable materials. Bottom ash and boiler slag possess unique physical and engineering properties that are different from conventional construction materials, for which the standard test methods have been developed. Some new or modified test methods are needed to provide a more complete evaluation of bottom ash and/or boiler slag properties. This is especially the case with respect to abrasion loss characteristics and particle size degradation during compaction for bottom ash.

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INTRODUCTION

Coal bottom ash and, to a lesser extent, boiler slag have been used as a granular base material for roads, streets, and parking areas on state, local, and private highway projects. To be successfully used in this application, the bottom ash (or boiler slag) must be able to satisfy conventional material specifications for gradation, soundness, and abrasion loss.

PERFORMANCE RECORD

Recent statistics for coal ash utilization indicate that, in 1996, approximately 0.6 million metric tons (0.7 million tons) of bottom ash were used as road base or subbase materials.(1) The road base and subbase category includes use as a granular or unbound base course, as well as stabilized base or subbase. A 1992 survey of all 50 state highway and transportation agencies indicated that at least four states have recently made use of bottom ash or boiler slag as a granular base material. These states are Georgia, Texas, Utah and Wyoming.(2) Wyoming has reportedly discontinued its use of bottom ash for this purpose because of reportedly poor performance. The other three states have indicated satisfactory performance.

Bottom ash and/or boiler slag have also been used in the past as an aggregate in unbound base course applications in other states, although not necessarily on state highway projects. Many such non-state installations are not well documented. Table 4-6 presents a list identifying a number of locations where the use of bottom ash and boiler slag has been documented.

In general, pavements using bottom ash or boiler slag as a granular base have reportedly performed in a satisfactory manner.

MATERIAL PROCESSING REQUIREMENTS

Dewatering (Moisture Control)

Bottom ash may require stockpiling for a short period of time (at least 1 or 2 days) to allow excess water to drain. Ponded ash reclaimed from a lagoon should be stockpiled and allowed to drain for a somewhat longer time period, perhaps up to 1 or 2 weeks, depending on the amount of rainfall. The ash should not be allowed to become too dry before use. If the ash becomes dusty while in a stockpile, or if dust is generated when the ash is being handled or loaded, it has become too dry and should be wetted enough to suppress further dusting before being used.

Table 4-6. General design and construction data for selected bottom ash/boiler slag granular base applications.

Project (Date)	Application	Quantity	Materials
Route 2[3] Moundsville, WV (1972)	6.4 km (4 mi) 229 mm (9 in) Granular Base	404,000 metric tons (225,000 tons)	Boiler Slag: 80 - 85% Blast Furnace Slag: 10 - 15%
Interstate 79[4] Bridgeport, WV (1972)	5.6 km (3.5 mi) 229 mm (9 in) Granular Base	161,000 metric tons (178,000 tons)	Bottom Ash
Highway 18[5] Saskatchewan, Canada (1976, 7)	2.9 km (1.8 mi) 533 mm (21 in) Granular Base	32,000 metric tons (35,000 tons)	Pond Ash Mix of Bottom Ash and Fly Ash
Highway 47[5] Estevan, WV (1977)	25.7 km (16.1 mi) 250 mm (10 in) Granular Base	135,000 metric tons (150,000 tons)	Pond Ash Mix of Bottom Ash and Fly Ash
Subdivision Development[6] Cartersville, GA (1982)	101 mm (4 in) Granular Base	1150 m^3 (1500 yd^3)	Bottom Ash

Screening

After size reduction, bottom ash can be screened to produce different size ranges, if desired. Boiler slag is more uniformly graded and usually does not require any screening prior to use. Blending with conventional aggregate may be required to meet specifications.

Deleterious Materials

Deleterious materials, such as soluble sulfates or coal pyrites, should be removed from the bottom ash, boiler slag, or pond ash before attempting to use these materials in a base course or subbase application. Pyrites can be removed from the coal before it is burned using sink-float techniques, or from the bottom ash or boiler slag using magnetic separation.

ENGINEERING PROPERTIES

Some of the engineering properties of bottom ash and/or boiler slag that are of particular interest when bottom ash and/or boiler slag are used as an aggregate in granular base applications are gradation, specific gravity and unit weight, moisture-density relationship, degradation under compaction, shear strength, bearing strength, and corrosivity.

Gradation: Bottom ash and boiler slag are considered to be fine aggregates.(7,8) Sometimes, in order to improve the sizing characteristics of the bottom ash or boiler slag, a conventional aggregate or a slag aggregate may be blended with the ash prior to its use in a base or subbase. Table 4-7 lists recommended size limits for bottom ash or boiler slag when used as a granular base material.(9)

Table 4-7. Recommended gradation for bottom ash or boiler slag used as granular base material.

Sieve Size	Percent Passing
19 mm (3/4 in)	100
9.5 mm 3/8 in)	70 - 90
44.75 mm (No. 4)	55 - 90
2.36 mm (No. 8)	40 - 70
1.18 mm (No. 16)	30 - 60
0.075 mm (No. 200)	0 - 30

Specific Gravity: The specific gravity of bottom ash usually ranges from 2.1 to 2.7,(10) but values as low as 1.9 and as high as 3.4 have been recorded.(11) Bottom ash with relatively low specific gravity (below 2.2) is often indicative of the presence of porous "popcorn" particles. Bottom ash with relatively high specific gravity (above 3.0) may indicate a high iron content.

The specific gravity of boiler slag usually ranges from 2.3 to 2.9. The dry unit weight of boiler slag usually ranges from 960 to 1440 kg/m^3 (60 to 90 lb/ft^3), whereas the dry unit weight of bottom ash may range from 720 to 1600 kg/m^3 (45 to 100 lb/ft^3).(10) Occasionally, the dry unit weight of bottom ash may reach 1840 kg/m^3 (115 lb/ft^3) and the dry unit weight of boiler slag may reach 1760 kg/m^3 (110 lb/ft^3).(11)

Moisture-Density Relationship: The laboratory moisture-density curves for dry bottom ash are similar in shape to those of typical cohesionless materials. These curves are characterized by a fairly high dry density for the air-dried condition, a lower dry density at intermediate moisture, and a high dry density at or near saturation. Generally, field compaction curves also exhibit maximum dry density at either an air-dried condition or a "flushed" or wet condition. It is recommended that bottom ash be maintained in a "flushed" condition in order to attain the highest degree of densification.(11) When compared with conventional granular materials, bottom ashes have lower maximum dry densities.(12)

Degradation Under Compaction: To quantify the extent of degradation under compaction, an index of crushing has been developed by calculating the mean size of a material before and after compaction and expressing the index of crushing as the percent reduction between the two mean sizes. The higher the index, the easier it is to crush the material. The index of crushing for pulverized coal bottom ash has been found to be roughly twice that of conventional aggregates, whereas the index of crushing for boiler slag is essentially the same as that of conventional aggregates. The index of crushing for bottom ash from a stoker-fired boiler was found to be about three times greater than the index of crushing for bottom ash from a pulverized coal boiler.(11)

Shear Strength: Bottom ash, because of its rough surface texture and angularity, has a slightly higher friction angle than conventional granular soils when it is compacted to a high relative density.(11) Direct shear tests conducted on dry bottom ash samples under loose and dense relative density conditions indicated that the angle of internal friction for most bottom ashes ranged from 35° to 50°, depending on the extent of densification, with some dense bottom ash samples exhibiting friction angles as high as 55°. The angle of internal friction for boiler slag was found to fall within the same range as that of most natural granular soils (between 36° and 46°).

Bearing Strength: California Bearing Ratio (CBR) testing of bottom ashes has indicated that soaking does not negatively affect the CBR of bottom ash. The CBR values at high moisture contents were found to be higher (between 40 and 70 percent) than corresponding CBR values on the dry side (between 35 and 60 percent). These findings further suggest that it is advantageous to compact bottom ash or ponded ash in a "flushed" or wet condition.(11) Typical CBR values for conventional granular base materials are in the range of 40 to 80 percent.

Corrosivity: When using bottom ash and/or boiler slag as a base or subbase material, there is the potential that metal structures that come into contact with the base or subbase material may eventually corrode.(13) The parameters of a base or subbase material that are most closely related to corrosivity are pH, electrical resistivity, soluble chlorides, and soluble sulfates. A study of 11 bottom ash or boiler slag samples from Indiana indicated that, using the above criteria, seven of the samples were considered corrosive, principally because of low electrical resistivity.(13) All bottom ash and boiler slag materials (including reclaimed ponded ash) being considered for prospective use as an unbound or granular base or subbase material should be investigated for corrosivity prior to use.

DESIGN CONSIDERATIONS

When using bottom ash or boiler slag (including reclaimed ponded ash) as an unbound or granular base/subbase material, the use of the AASHTO structural equivalency design method(14) is recommended as a granular base design procedure for either flexible or rigid pavements, whichever is applicable.

A layer coefficient value of 0.10 is recommended for the design of flexible pavement systems in which bottom ash, boiler slag, or reclaimed ponded ash is used to construct an unbound or granular base or subbase. A coefficient of 0.10 for these materials recognizes that they are not structurally equivalent to crushed stone, which is typically given a layer coefficient of 0.15.

CONSTRUCTION PROCEDURES

Material Handling and Storage

Both bottom ash and boiler slag can be handled and stored or stockpiled using the same methods and equipment that are normally used for handling and storage of conventional aggregates.

Placing and Compacting

Bottom ash and/or boiler slag can be dumped and spread with a motor grader or bulldozer or, preferably, placed into a spreader box or paving machine for more accurate grade control. The material can be spread and compacted very well when placed at, or slightly above, the optimum moisture content, as determined by standard Proctor compaction procedures.(15) However, bottom ash loses stability when it dries out, making it necessary to keep the material wet (or "flushed") so that construction equipment can operate satisfactorily on its surface.(10)

Compaction of bottom ash and boiler slag bases and subbases can be accomplished by static steel-wheel or pneumatic rollers, as well as vibratory compaction equipment. The material, regardless of whether it is bottom ash, boiler slag, or reclaimed pond ash, must be kept moist during and after compaction.(15) However, no matter how well the material has been compacted, it is still possible that some material may become unstable upon drying. The addition of up to 30 percent fines in the form of fly ash may remedy the loss of stability upon drying.(10)

Once a bottom ash granular base layer has been properly compacted, it must be protected. A prime coat of asphalt emulsion can be applied to the top surface of the base material to prevent rapid moisture evaporation, stabilize the surface, and provide a bond between the base layer and an asphalt or Portland cement concrete wearing surface.(5) An asphalt binder and/or wearing surface or a concrete pavement should be installed within a reasonable time after sealing the granular base layer in order to minimize traffic on this layer.

UNRESOLVED ISSUES

Bottom ash and/or boiler slag aggregates possess somewhat unique engineering properties and characteristics when compared more conventional sources of aggregate materials. For example, bottom ash may contain some particles that may crush or degrade easily, and boiler slag is very uniformly graded. Standard test methods and specifications have been developed to evaluate conventional aggregate materials. Some sources of bottom ash and/or boiler slag, although they may provide satisfactory performance as an aggregate in granular base material applications, are not always able to satisfy all test criteria and/or specification requirements for such aggregates. This is particularly the case as far as particle size distribution specifications and abrasion loss requirements for granular base courses are concerned.

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INTRODUCTION

Bottom ash and/or boiler slag can be used as either the fine aggregate fraction or, in some cases, as the entire aggregate in either Portland cement or pozzolan-stabilized base and subbase mixtures. A blend of bottom ash and boiler slag may comprise the entire aggregate portion of the mix if both materials are available. If only bottom ash is available, it may be used as the entire source of aggregate, or it may be blended with a coarse aggregate to meet a specified range of gradation. If only boiler slag is available, it must be blended with sand or other well-graded fine aggregate to produce an aggregate with a suitable particle size distribution. If a broader range of particle sizes is specified, further blending with a coarse aggregate may also be necessary.

PERFORMANCE RECORD

Bottom ash and, in particular, boiler slag have been used as aggregate sources in stabilized base or subbase applications since as far back as 40 years ago. Most of these installations have not been well documented, but their service record is believed to have been from fair to very good.

A recent survey reported that in 1996, 0.6 million metric tons (0.7 million tons) of bottom ash and/or boiler slag (predominantly bottom ash) were used as road base or subbase materials.(1) The category for road base or subbase includes stabilized base or subbase, as well as granular or unbound base or subbase installations. The exact percentage used in stabilized base applications was not reported.

According to a 1992 survey of all state highway and transportation agencies, at least five states indicated that they were currently making use of bottom ash or boiler slag in some type of stabilized base or subbase applications.(2) These states include Arkansas, Kentucky, Mississippi, Texas, and Utah. A sixth state, Wyoming, indicated some use of bottom ash as a granular base, but cited instability of the material as the reason for discontinuing the use of bottom ash. Although the nature of the instability was not explained, it is believed to be due to a lack of cohesion in the base, possibly because of the material becoming too dry.

Bottom ash and boiler slag have been used in the past as an aggregate for stabilized base and subbase mixtures in other states, although not necessarily on state highway projects. These states include, but are not limited to, Georgia, Illinois, Michigan, North Dakota, Ohio, and West Virginia. There are currently no state specifications for the use of bottom ash or boiler slag as an aggregate in stabilized base or subbase mixtures. Table 4-8 presents a listing of pertinent data on some selected applications.

Table 4-8. Pozzolanic stabilized base general design and construction data.

Project (Date)	Type	Constituents	Compressive Strength Data	
State Rt. 195(4) Montgomery County, Illinois (1976)	5.6 km (3.5 mi) 250 mm (10 in) Lime-Fly Ash Base Course	Lime - 3% Class F Fly Ash - 32.5% Boiler Slag - 64.5% (minus 4.75 mm (No. 4) sieve)	Lab (7 day) Cores (1 yr)	>6900 kPa (1000 lb/in^2) 9700 kPa (1400 lb/in^2)
Route 2(5) Wheeling, West Virginia (1971-1972)	Portland Cement, Boiler Ash, Bottom Ash Base Course	Aggregate Boiler Slag - 54% Bottom Ash - 46% Portland Cement - 5% (wt of aggregate)	No data	
Route 34(6) Charleston, West Virginia	Portland Cement Bottom Ash	No Data	Cores (2 yr)	>9000 kPa (1300 lb/in^2)
Rome, Georgia(7) (early 1980's)	305 mm (12 in) Lime Bottom Ash Base Course	Lime - 6 - 8%	Cores (6 wk)	>4800 kPa (700 lb/in^2)
Route 22(8) Georgia (1985)	305 m (1000 ft) 216 mm (8-1/2 in) Portland Cement Pond Ash Base Course	No Data	Lab (7 day)	3400 kPa (494 lb/in^2)
Route 15 Stone County Mississippi (1987)	Lime Stabilized Base and Portland Cement Stabilized Base with Class C Pond Ash	Lime - 2 - 7% Cement - 7.5%	7% Lime Base Cores Cement Base Cores	4500 - 8700 kPa (650 - 1260 lb/in^2) 15900 kPa (2300 lb/in^2)

Pozzolan-stabilized base compositions consisting of lime, fly ash, and aggregates (LFA) were originally patented in the early 1950's under the trade name Poz-O-Pac. Some of the first LFA compositions in the Chicago area were mixed in place and used boiler slag as the aggregate. These early mixtures contained an average of 5 percent by weight hydrated lime, 35 percent Class F fly ash, and 60 percent boiler slag. Pavements using such mixtures provided many years of satisfactory service, and cores taken from these pavements have developed compressive strengths well in excess of 6900 kPa (1,000 lb/in^2)(3)

Typical of these early boiler slag mixes was a 5.6 km (3.5 mile) service road built from State Route 195 to the Coffeen power station near Coffeen, Illinois, during the mid-1970's. General design and construction data are presented in Table 4-8. The pavement reportedly performed without distress, even though the roadway was constantly subjected to heavy truck traffic.(4)

The first known large-scale use of a cement-stabilized bottom ash base course in the United States was in the relocation of West Virginia Route 2 during the 1971-72 construction season. The aggregate used was a blend of bottom ash and boiler slag from American Electric Power Company's Mitchell and Kammer plants, respectively. General design and construction data are presented in Table 4-8. The blend was necessary in order to meet the West Virginia Department of Highway gradation specifications for cement-treated base course. The roadway provided excellent service for over 10 years at a substantial reduction in cost compared with the use of conventional aggregates.(5)

Since 1984 several hundred miles of low-volume secondary roads in West Virginia have been reconstructed using cement-stabilized bottom ash. Most of these roads were primarily gravel subbase with traffic ranging from 150 to 1,500 vehicles per day. A typical section, presented in Table 4-8, is Route 34 in Putnam County, near Charleston, where a 150 mm (6 in) thick bottom ash subbase was placed and compacted. Successive 150 mm (6 in) thick lifts of cement-treated bottom ash were placed on top of the subbase.(6)

During the early 1980's, Georgia Power Company successfully constructed a lime-stabilized bottom ash base with a 38 mm (1-1/2 in) asphalt wearing surface near Rome, Georgia.(7) In 1985, the Georgia Department of Transportation successfully constructed a 305 m (1,000 ft) section of cement stabilized pond ash base on State Route 22.(8)

In 1987, pond ash from subbituminous coal was used to reconstruct approximately 2.4 km (1.5 miles) of State Route 15 in Stone County, Mississippi. The reconstruction involved five different sections, four with lime-stabilized ash and one with cement-stabilized ash. A 1.36 km (0.85 mile) control section of mechanically stabilized sand-clay subbase was also constructed. All sections were mixed in place and had a double bituminous surface treatment as a wearing surface. Stabilized base design data are presented in Table 4-8.

Deflection measurements were taken each year after construction through 1990. The sections with 6 and 7 percent lime and 7.5 percent cement all had much lower deflection readings than the control section and the section with only 2 percent lime. After 3 years of service, the control section and the section with 2 percent lime had no observed cracking, while the cement stabilized section had the most cracking.(9) The shrinkage cracking of cement-stabilized granular materials is a fairly common occurrence, especially in soil-cement mixtures. The cracking in traditional soil-cement mixtures is attributable to the hydration of Portland cement. None of the cracking that was observed was considered structural in nature.

MATERIAL PROCESSING REQUIREMENTS

Dewatering

Bottom ash and/or boiler slag are both well-drained materials that can be readily dewatered in 1 or 2 days. Ponded ash reclaimed from a lagoon for use as a base course aggregate should be stockpiled and allowed to drain prior to use. Ponded ash will require a longer dewatering period because it usually includes some fly ash. The higher the percentage of fly ash in the ponded ash, the longer will be the time required for dewatering.

Crushing or Screening

Well-graded aggregates normally require less activator or reagent than poorly graded aggregates in order to produce a well-compacted mixture. Bottom ash is generally a more well-graded aggregate than boiler slag, which is normally more uniformly graded between the 4.75 mm (No. 4) and 0.42 mm (No. 40) sieve sizes. Pond ash may be a blend of bottom ash and fly ash, and will vary in gradation, depending on its location in the pond relative to the discharge pipe. Bottom ash may contain some agglomerations or "popcorn" particles. These agglomerations should either be reduced in size by clinker grinders at the power plant or removed by scalping or screening at the 12.7 mm (1/2 in) or 19 mm (3/4 in) screen.

Blending

When necessary to achieve a specified gradation, bottom ash or boiler slag may need to be blended with other aggregates. This is normally not necessary with bottom ash, but may be necessary with boiler slag.

Removal of Deleterious Materials

Deleterious materials, especially coal pyrites, should be removed at the power plant prior to use of bottom ash or boiler slag as an aggregate. The pyrites oxidize (or weather) over time, causing expansion and possible popouts of individual particles from the matrix. Soluble sulfates also occur in some bottom ashes. Low pH values are often used as an indicator for the presence of sulfates.(10)

ENGINEERING PROPERTIES

Some of the engineering properties of bottom ash and/or boiler slag that are of particular interest when used as aggregates in stabilized base or subbase mixtures are gradation, specific gravity and unit weight, durability, and soundness.

Gradation: The size limits in Table 4-9 are recommended for cement-treated aggregate base by the Portland Cement Association(11) and are applicable to bottom ash and/or boiler slag use in cement-treated base course mixes.

Table 4-9. Recommended gradation for cement stabilized base.

Sieve Size	Percent Passing
19 mm (3/4 in)	100
9.5 mm (3/8 in)	70-90
4.75 mm (No. 4)	55-90
3.35 mm (No. 8)	40-70
1.18 mm (No. 16)	30-60
0.075 mm (No. 200)	0-30

Specific Gravity and Unit Weight: The specific gravity of bottom ash usually ranges from 2.1 to 2.7, with dry unit weights ranging from 720 to 1600 kg/m^3 (45 to 100 lb/ft^3). The specific gravity of boiler slag usually ranges from 2.3 to 2.9, with dry unit weights ranging from 960 to

1440 kg/m^3 (60 to 90 lb/ft^3).(5) With bottom ash, lower specific gravity is usually indicative of the presence of porous "popcorn" particles, which readily degrade under compaction.

Durability: In ASTM C131(12) (Los Angeles Abrasion) tests, bottom ash has had loss values between 30 and 50 percent. Boiler slag has had loss values between 24 and 48 percent.(16) Most bottom ashes have loss values less than 45 percent,(13) enabling them to meet ASTM requirements for soil-aggregate base and subbase materials.(14)

Soundness: The durability of an aggregate for possible use in stabilized bases or subbases can be evaluated by the sodium sulfate soundness test.(15) Bottom ash has had sodium sulfate soundness loss values that normally range from 1.5 to 10.5 percent. Boiler slag has had sodium sulfate soundness loss values of between 1 and 9 percent.(16) The lower the specific gravity, the higher the probable percentage of deleterious material in the ash, which will likely be reflected in a higher value for soundness loss.

DESIGN CONSIDERATIONS

Mix Design

For pozzolan-stabilized base (PSB) mixtures containing coal fly ash (along with either lime, Portland cement, or kiln dust as an activator), the initial step in determining mix design proportions is to find the optimum fines content. This is done by progressively increasing the percentage of fines and determining the compacted density of each blend. Fly ash alone can be used to represent the total fines. A Proctor mold and standard compaction procedures are used for each blend of bottom ash and/or boiler slag and fines. Fly ash percentages ranging from 25 to 45 percent by dry weight of the total blend are suggested for the initial trial mixes.

At least three different fly ash additions are needed to establish the optimum fines content, which is the percentage of fines that results in the highest compacted dry density. The dry density for each fly ash percentage is then plotted to identify the optimum fines content. An optimum moisture content must then be determined for the selected mix design proportions.

Once the design fly ash percentage and optimum moisture content have been determined, the activator (lime, Portland cement, kiln dust, etc.) percentage must also be established. Trial mixtures using a gradual increase in the activator percentage are recommended. Final mix proportions are selected based on the results of compressive strength and durability testing, using

ASTM C593 procedures.(17) The objective is to meet strength and durability criteria with the most economical mix design.

For cement-stabilized bottom ash and/or boiler slag mixtures, the only mix design consideration is a determination of the percentage of Portland cement to be added to the mixture. As with the PSB mixtures, trial mixtures using several increasing percentages of cement will be necessary. Usually between 5 and 12 percent Portland cement will be needed to properly stabilize bottom ash and/or boiler slag for use as a roller-compacted base course. The results of ASTM C593 compressive strength and durability testing should be the basis for selection of final mix proportions.

The compacted unit weight of bottom ash and/or boiler slag mixes is usually considerably lower than the compacted unit weight of stabilized base mixtures containing conventional aggregates. Consequently, a cement content of 10 percent by weight for a base course mix containing bottom ash and/or boiler slag may be the equivalent of a 7 percent by weight cement content for a similar mix containing a normal weight aggregate.

In general, the trial mixture with the lowest percentage of cement (or activator plus fly ash in PSB mixtures) that satisfies both the compressive strength and the durability criteria is considered the most economical mixture. To ensure an adequate factor of safety for field placement, it is recommended that the stabilized base or subbase mixture used in the field have an activator content that is at least 0.5 percent higher (1.0 percent higher if using kiln dust) than that of the most economical mixture.(18)

Structural Design

The thickness design of stabilized base or subbase mixtures containing bottom ash or boiler slag can be undertaken using the standard structural equivalency design method for flexible pavements described in the AASHTO Design Guide.(19) This method uses an empirical structural number (SN) that relates pavement layer thickness to performance.

Table 4-10 lists recommended structural coefficient values based on studies of pozzolanic and crushed stone base materials(19) for stabilized base or subbase mixtures. The values are for stabilized base or subbase materials that attain a given range of compressive strength, regardless of the source of aggregate used or the type of reagent(s) in the design mix. These coefficient values are based on the use of $a_1 = 0.44$ (used for a bituminous wearing surface) and a value of $a_3 = 0.15$ (used for a crushed stone base).

Table 4-10. Recommended structural layer coefficient values for stabilized base and subbase materials.

Quality	Compressive Strength, psi (7 days @ 37.7°C)	Recommended Structural Layer Coefficient
High	Greater than 1,000	$a_2 = 0.34$
Average	650 to 1,000	$a_2 = 0.28$
Low	400 to 650	$a_2 = 0.20$

The main factors influencing the selection of the structural layer coefficient are the compressive strength and modulus of elasticity of the stabilized base material. The value of compressive strength recommended for determination of the structural layer coefficient is the field design compressive strength, which is the compressive strength developed in the laboratory after 56 days of moist curing at 73 °F (23 °C).(18) However, other time and temperature curing conditions may be required by various specifying agencies.

When a Portland cement concrete (PCC) roadway surface is to be designed with a stabilized base or subbase, the AASHTO structural design method for rigid pavements can be used.(19)

CONSTRUCTION PROCEDURES

Material Handling and Storage

Both bottom ash and boiler slag can be handled and stored using the same methods and equipment that are normally used for handling and storage of conventional aggregates.

Mixing, Placing, and Compacting

The blending or mixing of bottom ash or boiler slag in stabilized base mixtures can be done either in a mixing plant or in place. Plant mixing is recommended because it provides greater control over the quantities of materials batched and also results in the production of a more uniform mixture. Although mixing in place does not usually result in as accurate a proportioning of mix components as plant mixing, it is probably used more frequently with mixes involving bottom ash or boiler slag and will still produce a satisfactory stabilized base material.

Stabilized base materials should not be placed in layers that are less than 100 mm (4 in) or greater than 200 to 225 mm (8 to 9 in) in compacted thickness. These materials should be spread in loose layers that are approximately 50 mm (2 in) greater in thickness prior to compaction than the desired compacted thickness. The top surface of an underlying layer should be scarified prior to placing the next layer. For granular or coarse-graded mixtures, steel-wheeled vibratory rollers are most frequently used for compaction. For more fine-grained mixtures, a vibratory sheepsfoot roller, followed by a pneumatic roller, is often employed.(18)

To develop the design strength of a stabilized base mixture, the material must be well-compacted and must be as close as possible to its optimum moisture content when placed. Plant-mixed materials should be delivered to the job site as soon as possible after mixing and should be compacted within a reasonable time after placement.

When self-cementing fly ashes are used as a cementitious material in stabilized base mixtures, compaction should be accomplished as soon as possible after mixing. Otherwise, delays between placement and compaction of such mixtures may be accompanied by a significant decrease in the strength of the compacted stabilized base material, unless a retarder is used. A commercial retarder, such as gypsum or borax, may be added at the mixing plant in low percentages (approximately 1 percent by weight) without adversely affecting the strength development of the stabilized base material.(18)

Curing

After placement and compaction, the stabilized base material must be properly cured to protect against drying and to assist in the development of in-place strength. An asphalt emulsion seal coat should be applied to the top surface of the stabilized base or subbase material within 24 hours after placement. The same practice is applicable if a PCC pavement is to be constructed above the stabilized base or subbase material. Placement of asphalt paving over the stabilized base is recommended within 7 days after the base has been installed. Unless an asphalt binder and/or surface course has been placed over the stabilized base material, it is recommended that vehicles should not be permitted to drive over the material until it has achieved an in-place compressive strength of at least 2400 kPa (350 lb/in^2).(18)

Special Considerations

Cold Weather Construction: Stabilized base materials containing bottom ash and/or boiler slag that are subjected to freezing and thawing conditions must be able to develop a certain level of cementing action and in-place strength prior to the first freeze-thaw cycle in order to withstand the disruptive forces of such cycles. For northern states, many state transportation agencies have established construction cutoff dates for stabilized base materials. These cutoff dates ordinarily range from September 15 to October 15, depending on the state, or the location within a particular state, as well as the ability of the stabilized base mixture to develop a minimum desired compressive strength within a specified time period.(19)

Crack Control Techniques: Stabilized base materials, especially those in which Portland cement is used as the activator, are subject to cracking. The cracks are almost always shrinkage related and are not the result of any structural weakness or defects in the stabilized base material. The cracks also do not appear to be related to the type of aggregate used in the base mix. Unfortunately, shrinkage cracks eventually reflect through the overlying asphalt pavement and must be sealed at the pavement surface to prevent water intrusion and subsequent damage due to freezing and thawing.

One approach to controlling or minimizing reflective cracking associated with shrinkage cracks in stabilized base materials is to saw cut transverse joints in the asphalt surface that extend into the stabilized base material to a depth of 75 mm (3 in) to 100 mm (4 in). Joint spacings of 9 m (30 ft) have been suggested.(18) The joints should all be sealed using a hot poured asphaltic joint sealant.

UNRESOLVED ISSUES

As noted above, control of shrinkage cracking has been long considered by many state transportation agencies as a prime concern associated with stabilized base mixtures, especially cement-stabilized mixtures. Since most mixtures that include bottom ash and/or boiler slag as the aggregate have been placed on secondary roads, haul roads, and parking lots, as opposed to higher-type highway facilities, the issue of crack control has not been as great a concern to the owners or administrators of these installations. However, additional mix designs with reduced potential for shrinkage cracking need to be developed, especially if these materials are someday to be used on higher-type facilities.

Pyrites must be removed before bottom ash or boiler slag can be used. Soluble sulfates in bottom ash may warrant removal if found in sufficient quantity to be considered detrimental. Improved techniques for timely removal of these detrimental constituents are needed.

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ORIGIN

The fly ash produced from the burning of pulverized coal in a coal-fired boiler is a fine-grained, powdery particulate material that is carried off in the flue gas and usually collected from the flue gas by means of electrostatic precipitators, baghouses, or mechanical collection devices such as cyclones.

In general, there are three types of coal-fired boiler furnaces used in the electric utility industry. They are referred to as dry-bottom boilers, wet-bottom boilers, and cyclone furnaces. The most common type of coal burning furnace is the dry-bottom furnace.

When pulverized coal is combusted in a dry-ash, dry-bottom boiler, about 80 percent of all the ash leaves the furnace as fly ash, entrained in the flue gas. When pulverized coal is combusted in a wet-bottom (or slag-tap) furnace, as much as 50 percent of the ash is retained in the furnace, with the other 50 percent being entrained in the flue gas. In a cyclone furnace, where crushed coal is used as a fuel, 70 to 80 percent of the ash is retained as boiler slag and only 20 to 30 percent leaves the furnace as dry ash in the flue gas.[1] A general flow diagram of fly ash production in a dry-bottom coal-fired utility boiler operation is presented in Figure 5-1.

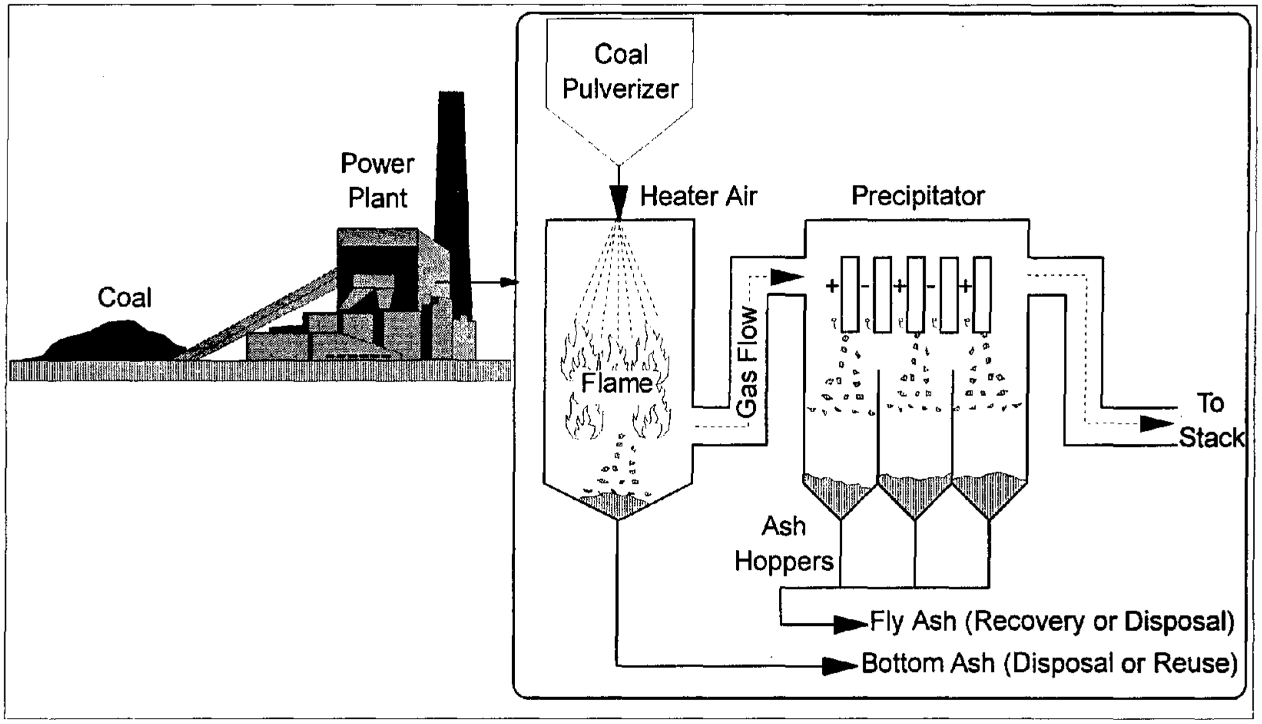

Figure 5-1. Production of fly ash in a dry-bottom utility boiler with electrostatic precipitator.

During 1996, the most recent year for which ash statistics are currently available, the electrical utility industry in the United States generated approximately 53.5 million metric tons (59.4 million tons) of coal fly ash. Until 1996, the amount of fly ash produced annually had remained roughly the same since 1977, ranging from 42.9 to 49.7 million metric tons (47.2 to 54.8 million tons).(2)

Additional information on coal ash use in the United States can be obtained from:

American Coal Ash Association (ACAA)
2760 Eisenhower Avenue, Suite 304
Alexandria, Virginia 22314

Electric Power Research Institute
3412 Hillview Road
Palo Alto, California 94304

Edison Electric Institute
1701 Pennsylvania Avenue, N.W.
Washington, D.C. 20004-2696

CURRENT MANAGEMENT OPTIONS

Recycling

In 1996, approximately 14.6 million metric tons (16.2 million tons) of fly ash were used. Of this total, 11.85 million metric tons (13.3 million tons), or approximately 22 percent of the total quantity of fly ash produced, were used in construction-related applications. Table 5-1 lists the leading construction applications in which fly ash was used during 1996.

Between 1985 and 1995, fly ash usage has fluctuated between approximately 8.0 and 11.9 million metric tons (8.8 and 13.6 million tons) per year, averaging 10.2 million metric tons (11.3 million tons) per year.(3) Fly ash is useful in many applications because it is a pozzolan, meaning it is a siliceous or alumino-siliceous material that, when in a finely divided form and in the presence of water, will combine with calcium hydroxide (from lime, Portland cement, or kiln dust) to form cementitious compounds.(4)

Disposal

Approximately 70 to 75 percent of fly ash generated is still disposed of in landfills or storage lagoons.(2) Much of this ash, however, is capable of being recovered and used.

Table 5-1. Fly ash construction-related applications (1996).

Applications	Quantity Used		Percent of Total Used
	Million Metric Tons	Million Tons	
Cement production and/or concrete products	7.2	8.0	60
Structural fills or embankments	1.9	2.2	17
Stabilization of waste materials	1.7	1.9	14
Road base or subbase materials	0.63	0.7	5
Flowable fill and grouting mixes	0.27	0.3	2
Mineral filler in asphalt paving	0.15	0.2	2
Approximate Total	11.85	13.3	100

MARKET SOURCES

Although electric utility companies produce ash at their coal-fired power plants, most utilities do not handle, dispose of, and/or sell the ash that they produce. There are approximately 40 to 50 commercial ash marketing firms operating throughout the United States, in all states except Hawaii. In addition to commercial ash marketing organizations, certain coal-burning electric utility companies have formal ash marketing programs of their own. Most coal-burning electric utility companies currently employ an ash marketing specialist whose responsibility it is to monitor ash generation, quality, use or disposal, and to interface with the ash marketers or brokers who are under contract to the utility companies.

Because of variations in coals from different sources, as well as differences in the design of coal-fired boilers, not all fly ash is the same. Although there may be differences in the fly ash from one plant to another, day-to-day variations in the fly ash from a given power plant are usually quite predictable, provided plant operation and coal source remain constant. However, there can be a substantial variation in fly ash obtained from burning coal with other fuels (such as natural gas or wood) or with other combustible materials (such as municipal solid waste, scrap tires, etc.). As long as the basic operating parameters at the power plant do not change, fly ash from a known source that is supplied by a reputable ash marketing organization should be a consistent, quality-controlled product.

Fly ash to be used in Portland cement concrete (PCC) must meet the requirements of ASTM C618.(5) Two classes of fly ash are defined in ASTM C618: 1) Class F fly ash, and 2) Class C fly ash.

Fly ash that is produced from the burning of anthracite or bituminous coal is typically pozzolanic and is referred to as a Class F fly ash if it meets the chemical composition and physical requirements specified in ASTM C618. Materials with pozzolanic properties contain glassy silica and alumina that will, in the presence of water and free lime, react with the calcium in the lime to produce calcium silicate hydrates (cementitious compounds).

Fly ash that is produced from the burning of lignite or subbituminous coal, in addition to having pozzolanic properties, also has some self-cementing properties (ability to harden and gain strength in the presence of water alone). When this fly ash meets the chemical composition and physical requirements outlined in ASTM C618, it is referred to as a Class C fly ash. Most Class C fly ashes have self-cementing properties.

Fly ash is typically stored dry in silos, from which it can be used or disposed of in a dry or wet form. Water can be added to the fly ash to allow for stockpiling or landfilling in a conditioned form (approximately 15 to 30 percent moisture), or for disposal by sluicing into settling ponds or lagoons in a wet form. Approximately 75 percent of the fly ash produced is handled in a dry or moisture-conditioned form, making it much easier to recover and use. The main advantage to the conditioning of fly ash is the reduction of blowing or dusting during truck transport and outdoor storage.

HIGHWAY USES AND PROCESSING REQUIREMENTS

Portland Cement Concrete – Supplementary Cementitious Material

Fly ash has been successfully used as a mineral admixture in PCC for nearly 60 years. This is the largest single use of fly ash. It can also be used as a feed material for producing Portland cement and as a component of a Portland-pozzolan blended cement.

Fly ash must be in a dry form when used as a mineral admixture. Fly ash quality must be closely monitored when the material is used in PCC. Fineness, loss on ignition, and chemical content are the most important characteristics of fly ash affecting its use in concrete. Fly ash used in concrete must also have sufficient pozzolanic reactivity and must be of consistent quality.

Asphalt Concrete – Mineral Filler

Fly ash has been used as a substitute mineral filler in asphalt paving mixtures for many years. Mineral filler in asphalt paving mixtures consists of particles, less than 0.075 mm (No. 200 sieve) in size, that fill the voids in a paving mix and serve to improve the cohesion of the binder (asphalt cement) and the stability of the mixture. Most fly ash sources are capable of meeting the gradation (minus .075 mm) requirements and other pertinent physical (nonplastic) and chemical (organic content) requirements of mineral filler specifications.

Fly ash must be in a dry form for use as a mineral filler. Fly ash that is collected dry and stored in silos requires no additional processing. It is possible that some sources of fly ash that have a high lime (CaO) content may also be useful as an antistripping agent in asphalt paving mixes.

Stabilized Base – Supplementary Cementitious Material

Stabilized bases or subbases are mixtures of aggregates and binders, such as Portland cement, which increase the strength, bearing capacity, and durability of a pavement substructure. Because fly ash may exhibit pozzolanic properties, or self-cementing properties, or both, it can and has been successfully used as part of the binder in stabilized base construction applications. When pozzolanic-type fly ash is used, an activator must be added to initiate the pozzolanic reaction. Self-cementing fly ash does not require an activator. The most commonly used activators or chemical binders in pozzolan-stabilized base (PSB) mixtures are lime and Portland cement, although cement kiln dusts and lime kiln dusts have also been used with varying degrees of success. Sometimes, combinations of lime, Portland cement, or kiln dusts have also been used in PSB mixtures.

The successful performance of PSB mixtures depends on the development of strength within the matrix formed by the pozzolanic reaction between the fly ash and the activator. This cementitious matrix acts as a binder that holds the aggregate particles together, similar in many respects to a low-strength concrete.

Flowable Fill – Aggregate or Supplementary Cementitious Material

Flowable fill is a slurry mixture consisting of sand or other fine aggregate material and a cementitious binder that is normally used as substitute for a compacted earth backfill. Fly ash has been used in flowable fill applications as a fine aggregate and (because of its pozzolanic properties) as a supplement to or replacement for the cement. Either pozzolanic or self-cementing fly ash can be used in flowable fill. When large quantities of pozzolanic fly ash are added, the fly ash can act as both fine aggregate and part of the cementitious matrix. Self-cementing fly ash is used in smaller quantities as part of the binder in place of cement.

The quality of fly ash used in flowable fill applications need not be as strictly controlled as in other cementitious applications. Both dry and reclaimed ash from settling ponds can be used. No special processing of fly ash is required prior to use.

Embankment and Fill Material

Fly ash has been used for several decades as an embankment or structural fill material, particularly in Europe. There has been relatively limited use of fly ash as an embankment material in this country, although its use in this application is becoming more widely accepted.

As an embankment or fill material, fly ash is used as a substitute for natural soils. Fly ash in this application must be stockpiled and conditioned to its optimum moisture content to ensure that the material is not too dry and dusty or too wet and unmanageable. When fly ash is at or near its optimum moisture content, it can be compacted to its maximum density and will perform in an equivalent manner to well-compacted soil.

MATERIAL PROPERTIES

Physical Properties

Fly ash consists of fine, powdery particles that are predominantly spherical in shape, either solid or hollow, and mostly glassy (amorphous) in nature. The carbonaceous material in fly ash is composed of angular particles. The particle size distribution of most bituminous coal fly ashes is generally similar to that of a silt (less than a 0.075 mm or No. 200 sieve). Although subbituminous coal fly ashes are also silt-sized, they are generally slightly coarser than bituminous coal fly ashes.(2)

The specific gravity of fly ash usually ranges from 2.1 to 3.0, while its specific surface area (measured by the Blaine air permeability method)(6) may range from 170 to 1000 m^2/kg.

The color of fly ash can vary from tan to gray to black, depending on the amount of unburned carbon in the ash. The lighter the color, the lower the carbon content. Lignite or subbituminous fly ashes are usually light tan to buff in color, indicating relatively low amounts of carbon as well as the presence of some lime or calcium. Bituminous fly ashes are usually some shade of gray, with the lighter shades of gray generally indicating a higher quality of ash.

Chemical Properties

The chemical properties of fly ash are influenced to a great extent by those of the coal burned and the techniques used for handling and storage. There are basically four types, or ranks, of coal, each of which varies in terms of its heating value, its chemical composition, ash content, and geological origin. The four types, or ranks, of coal are anthracite, bituminous, subbituminous, and lignite. In addition to being handled in a dry, conditioned, or wet form, fly ash is also sometimes classified according to the type of coal from which the ash was derived.

The principal components of bituminous coal fly ash are silica, alumina, iron oxide, and calcium, with varying amounts of carbon as measured by the loss on ignition (LOI). Lignite and subbituminous coal fly ashes are characterized by higher concentrations of calcium and magnesium oxide and reduced percentages of silica and iron oxide, as well as a lower carbon content, compared with bituminous coal fly ash.(7) Very little anthracite coal is burned in utility boilers, so there are only small amounts of anthracite coal fly ash.

Table 5-2 compares the normal range of the chemical constituents of bituminous coal fly ash with those of lignite coal fly ash and subbituminous coal fly ash. From the table, it is evident that lignite and subbituminous coal fly ashes have a higher calcium oxide content and lower loss on ignition than fly ashes from bituminous coals. Lignite and subbituminous coal fly ashes may have a higher concentration of sulfate compounds than bituminous coal fly ashes.

Table 5-2. Normal range of chemical composition for fly ash produced from different coal types (expressed as percent by weight).

Component	Bituminous	Subbituminous	Lignite
SiO_2	20-60	40-60	15-45
Al_2O_3	5-35	20-30	10-25
Fe_2O_3	10-40	4-10	4-15
CaO	1-12	5-30	15-40
MgO	0-5	1-6	3-10
SO_3	0-4	0-2	0-10
Na_2O	0-4	0-2	0-6
K_2O	0-3	0-4	0-4
LOI	0-15	0-3	0-5

In ASTM C618, fly ash for use in Portland cement concrete is classified as either Class F or Class C fly ash according to certain physical and chemical requirements. Although the Class F and Class C designations strictly apply only to fly ash meeting the ASTM C618 specification, these terms are often used more generally to apply to fly ash on the basis of its original coal type or CaO content. It is important to recognize that not all fly ashes are able to meet ASTM C618 requirements and that, for applications other than concrete, it may not be necessary for them to do so.

The chief difference between Class F and Class C fly ash (using the generally accepted connotations of these classifications, i.e., not strictly according to ASTM C618) is in the amount of calcium and the silica, alumina, and iron content in the ash.(6) In Class F fly ash, total calcium typically ranges from 1 to 12 percent, mostly in the form of calcium hydroxide, calcium sulfate, and glassy components in combination with silica and alumina. In contrast, Class C fly ash may have reported calcium oxide contents as high as 30 to 40 percent.(8) Another difference between Class F and Class C is that the amount of alkalis (combined sodium and potassium) and sulfates are generally higher in the Class C fly ashes than in the Class F fly ashes.

The loss on ignition (LOI), which is a measurement of the amount of unburned carbon remaining in the fly ash, is one of the most significant chemical properties of fly ash, especially as an indicator of suitability for use as a cement replacement in concrete.

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INTRODUCTION

Coal fly ash can be used as a mineral filler in hot mix asphalt paving applications. Asphalt mixtures containing low addition levels (approximately 5 percent by dry weight of aggregate) of fly ash as a mineral filler exhibit mix design properties that are usually comparable to asphalt mixtures containing natural fillers such as hydrated lime or stone dust. Gradation, organic impurities, and plasticity characteristics ordinarily associated with mineral filler specification requirements can normally be met without difficulty.

PERFORMANCE RECORD

Research conducted over many years has determined that fly ash is a suitable mineral filler material. The earliest study of this application dates back to 1931, when the Detroit Edison Company compared the physical properties of fly ash with those of limestone dust. Fly ash was shown to have comparable physical properties to limestone dust, to possess good void filling characteristics, and to be hydrophobic, meaning it sheds water easily, thus reducing the potential for asphalt stripping.(1)

The U.S. Bureau of Public Roads (now the Federal Highway Administration (FHWA)), compared the retained strength of asphalt mixes containing various mineral fillers by means of the immersion-compression test.(2) This test is used as an indicator to evaluate resistance to stripping. Four sources of fly ash were evaluated, along with silica dust, limestone dust, mica dust, and traprock dust. Similarly, North Dakota State University compared lignite fly ash as a mineral filler with hydrated lime and crusher dust.(3) In both investigations, mixes containing the fly ash fillers had higher retained strengths than the other filler sources tested, indicating that fly ash fillers can be expected to provide excellent resistance to stripping.(4)

Further confirmation of the beneficial anti-stripping characteristics of fly ash mineral fillers was provided from an investigation of two western coal fly ashes (one Class C and one Class F) in combination with, or as a replacement for, Portland cement or hydrated lime. All mixes which contained fly ash showed comparable or improved retained strengths in the immersion-compression test using two different sources of aggregate.(5)

A study of Texas lignite fly ash indicated that the use of these fly ashes as mineral filler retards the rate of age hardening of asphalt cement. The high lime content of these fly ashes also appears to be particularly beneficial as an anti-stripping agent for polish-susceptible aggregates.(6)

A 1994 survey of all 50 state transportation agencies indicated that eight states have made some recent use of fly ash as a mineral filler in asphalt paving. These states included Connecticut, Louisiana, Michigan, Nebraska, New York, Ohio, Oregon, and Pennsylvania. Most of these states reported that the performance of fly ash as a filler material was fair to good. However, in two states (Michigan and Nebraska), fly ash reportedly performed poorly as a filler material and was either discontinued or eliminated from further use.(7)

An earlier survey of all state transportation agencies in 1992 also indicated that eight states reported using fly ash as a filler. In that survey, Arkansas and Kansas were noted in place of Connecticut and Oregon. There were also two states that reported poor performance, these being Nebraska and New York.(8) It has also been indicated by at least one asphalt producer that using fly ash as a filler material during hot weather has resulted in tender mixes that tend to push or shove under the action of a steel-wheeled roller.(9)

Previous surveys of state transportation agencies by the American Coal Ash Association have indicated that at least 14 other states, besides those noted above, reported having used fly ash at one time or another as mineral filler. These states included Alabama, Arizona, Colorado, Illinois, Kentucky, Maryland, Minnesota, Montana, Nevada, New Mexico, North Carolina, North Dakota, West Virginia, and Wyoming. There is no indication from these surveys regarding fly ash performance. The American Coal Ash Association has reported that approximately 96,000 metric tons (107,000 tons) of fly ash were used in 1995 as a mineral filler in asphalt.(10)

MATERIAL PROCESSING REQUIREMENTS

Drying

Fly ash must be in a dry form when used as a mineral filler. This means that moisture-conditioned fly ash and reclaimed ponded fly ash are unsuitable for this application.

Storage

Fly ash is collected at the power plant and stored in silos in a dry form. As a result, it can readily be loaded into pneumatic hauling vehicles and delivered to a hot mix asphalt plant.

ENGINEERING PROPERTIES

The physical requirements for mineral filler in bituminous paving mixtures are defined in AASHTO M17 and are shown in Table 5-3.(11) These requirements include gradation, organic impurities, and plasticity characteristics. Other properties of interest include fineness and specific gravity.

Table 5-3. AASHTO M17 specification requirements for mineral filler use in asphalt paving mixtures.

Particle Sizing		Organic Impurities	Plasticity Index
Sieve Size	Percent Passing		
0.006 mm (No. 30)	100	Mineral filler must be free from any organic impurities	Mineral filler must have plasticity index not greater than 4
0.003 mm (No. 50)	95-100		
0.075 mm (No. 200)	70-100		

Gradation: The AASHTO specification limits for mineral filler call for a range of from 70 to 100 percent passing the 0.075 mm (No. 200) sieve. Most fly ashes typically fall within a size range of from 60 to 90 percent passing the 0.075 mm (No. 200) sieve.(12)

Fineness: Although most sources of fly ash are capable of meeting the AASHTO gradation requirements for mineral filler, consistency of gradation is also important, especially the size and shape of the particles finer than a 0.075 mm (No. 200) sieve. Theoretically, higher fineness may indicate a more effective mineral filler, although the higher fineness also means a greater surface area of particles that must be coated, resulting in an increase in asphalt content of the mix. Fly ash fineness is often specified by the percentage by weight retained on the 0.045 mm (No. 325) sieve, especially when used in Portland cement concrete;(13) however, this is not a standard for fly ash used as a mineral filler.

Specific Gravity: The specific gravity of fly ash varies from source to source. It may be as low as 1.7 to as high as 3.0, but is more often within a range of 2.0 to 2.8. Most conventional mineral fillers have a specific gravity in the 2.6 to 2.8 range; therefore, a given weight percentage of fly ash will usually occupy a greater volume than that of a conventional filler material.

Organic Impurities: Some fly ash from boilers that burn oil during start-up periods may have some residual oil in the fly ash. Although no standard for carbon content or loss on ignition (LOI) is specified for fly ash used as a mineral filler, it is probably more practical to use a fly ash with a relatively low LOI (less than 5 or 6 percent) to minimize the potential absorption of asphalt by carbonaceous particles.

Plasticity: Fly ash is a nonplastic material with no plasticity index.

DESIGN CONSIDERATIONS

Mix Design

The same mix design methods that are commonly used for hot mix asphalt paving mixtures are also applicable to mixes in which coal fly ash is used as a mineral filler. The percentage of fly ash filler to be incorporated into the design mix is the lowest percentage that will enable the mix to satisfy all the required design criteria.

One of the most recognized ways to improve the anti-stripping characteristics of an asphalt paving mix is the addition of a modest amount (usually ½ to 2 percent by weight) of commercial hydrated lime into the mix. Lignite or subbituminous fly ash contains up to 30 percent or more calcium, compared with anthracite or bituminous fly ash, which may only contain 4 to 6 percent of calcium. The use of high-calcium fly ash may improve asphalt stripping with many aggregates, although there is not a great amount of field performance data to corroborate this assumption.

Structural Design

Conventional AASHTO pavement structural design methods are applicable to asphalt pavements incorporating fly ash as a mineral filler in the mix.

CONSTRUCTION PROCEDURES

Material Handling and Storage

Fly ash is a dusty material and its use may result in more dust generation than that normally experienced from using conventional filler sources.

At a hot mix plant, the fly ash can be discharged directly into a storage silo, like conventional mineral fillers, prior to input into the mixing plant.

Mixing, Placing, and Compacting

The same methods and equipment used to mix, place, and compact conventional asphalt paving mixes are applicable for mixes containing fly ash.

In isolated instances, asphalt paving mixes with fly ash as the mineral filler have been observed to be tender and difficult to compact during hot weather. This does not appear to be a widespread problem and also does not appear to be universally true for all sources of fly ash during hot weather, or even at other times of the year.

UNRESOLVED ISSUES

Although most fly ash sources are capable of satisfying specification requirements for asphalt mineral filler, which relate mostly to particle sizing, not all fly ashes have performed satisfactorily in asphalt paving mixtures. The reasons for this are not altogether clear, but are probably related to the fineness of the fly ash, its chemical composition, and its affinity for the asphalt cement used in a paving mix. A better means of classifying fly ash for use as a mineral filler is needed.

A method for assessing the potential suitability of a given source of fly ash as a mineral filler in asphalt paving is needed. The loss on ignition (LOI) of fly ash, especially fly ash with a low calcium content, may not be a significant factor affecting its performance as a mineral filler. The calcium content, and in particular the free or available lime (CaO) content of fly ash with a high calcium content, is believed to be instrumental in its performance as a filler, especially as an aid in the prevention of asphalt stripping. Additional field performance data are needed to draw valid conclusions regarding these factors.

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INTRODUCTION

Coal fly ash has been successfully used in Portland cement concrete (PCC) as a mineral admixture, and more recently as a component of blended cement, for nearly 60 years. As an admixture, fly ash functions as either a partial replacement for, or an addition to, Portland cement and is added directly into ready-mix concrete at the batch plant. Fly ash can also be interground with cement clinker or blended with Portland cement to produce blended cements. ASTM C595(1) defines two blended cement products in which fly ash has been added: 1) Portland-pozzolan cement (Type IP), containing 15 to 40 percent pozzolan, or 2) Pozzolan modified Portland cement (Type I-PM), containing less than 15 percent pozzolan.

ASTM C618 defines two classes of fly ash for use in concrete: 1) Class F, usually derived from the burning of anthracite or bituminous coal, and 2) Class C, usually derived from the burning of lignite or subbituminous coal.(2) ASTM C618 also delineates requirements for the physical, chemical, and mechanical properties for these two classes of fly ash. Class F fly ash is pozzolanic, with little or no cementing value alone. Class C fly ash has self-cementing properties as well as pozzolanic properties.

PERFORMANCE RECORD

A 1992 survey of all 50 state transportation agencies indicated that 40 states have had experience in the use of fly ash as a mineral admixture in concrete, usually as a partial replacement for Portland cement, although a number of states have also used blended Portland-pozzolan cement. Virtually all 40 of these states have used fly ash in concrete pavements and shoulders. This same survey indicated that 44 states had specifications for the use of fly ash as a partial replacement for Portland cement in concrete.(3)

At the time of this survey, at least eight states did not permit the use of fly ash in either bridge deck or structural concrete. A number of states also did not permit the use of fly ash in white concrete items, such as curbs, sidewalks, and median barriers, and two states (Arkansas and New Mexico) reported questionable performance experience: Arkansas had temporarily discontinued the use of fly ash in bridge deck concrete, and New Mexico had a temporary moratorium on the use of Class C fly ash in concrete, pending further investigation.(4)

The principal benefits ascribed to the use of fly ash in concrete include enhanced workability due to spherical fly ash particles, reduced bleeding and less water demand, increased ultimate strength, reduced permeability and chloride ion penetration, lower heat of hydration, greater resistance to sulfate attack, greater resistance to alkali-aggregate reactivity, and reduced drying shrinkage.(5)

The main precautions usually associated with the use of fly ash in concrete include somewhat slower early strength development, extended initial setting time, possible difficulty in controlling air content, seasonal limitations during winter months, and quality control of fly ash sources.(5)

The use of Class F fly ash usually results in slower early strength development, but the use of Class C fly ash does not and may even enhance early strength development.

MATERIAL PROCESSING REQUIREMENTS

Source Control

To ensure the quality of fly ash for use in PCC, the following sources of ash should be avoided:

- Ash from a peaking plant instead of a base loaded plant.
- Ash from plants burning different coals or blends of coal.
- Ash from plants burning other fuels (wood chips, tires, trash) blended with coal.
- Ash from plants using oil as a supplementary fuel.
- Ash from plants using precipitator additives, such as ammonia.
- Ash from start-up or shut-down phases of operation.
- Ash from plants not operating at a "steady state."
- Ash that is handled and stored using a wet system.

The net result of all these restrictions is that only a relatively low percentage (25 to 30 percent, at most) of all the coal fly ash produced annually is even potentially suitable for use in PCC.

Drying or Conditioning

When used in blended cement or as a partial replacement for Portland cement in ready-mix concrete, fly ash must be in a dry form and as such requires no processing. When used as a raw feed material for the production of Portland cement, either dry or conditioned ash can be used.

Quality Control

Fly ash used in concrete should be as consistent and uniform as possible. Fly ash to be used in concrete should be monitored by a quality assurance/quality control (QA/QC) program that complies with the recommended procedures in ASTM C311.(6) These procedures establish standards for methods of sampling and frequency of performing tests for fineness, loss on ignition (LOI), specific gravity, and pozzolanic activity such that the consistency of a fly ash source can be certified.

Many state transportation agencies, through their own program of sampling and testing, have been able to prequalify sources of fly ash within their own state (or from nearby states) for acceptance in ready-mixed concrete. Prequalification of fly ashes from different sources provides an agency with a certain level of confidence in the event fly ashes from different sources are to be used in the same project.

ENGINEERING PROPERTIES

Some of the engineering properties of fly ash that are of particular interest when fly ash is used as an admixture or a cement addition to PCC mixes include fineness, LOI, chemical composition, moisture content, and pozzolanic activity. Most specifying agencies refer to ASTM C618(2) when citing acceptance criteria for the use of fly ash in concrete.

Fineness: Fineness is the primary physical characteristic of fly ash that relates to pozzolanic activity. As the fineness increases, the pozzolanic activity can be expected to increase. Current specifications include a requirement for the maximum allowable percentage retained on a 0.045 mm (No. 325) sieve when wet sieved. ASTM C618 specifies a maximum of 34 percent retained on a 0.045 mm (No. 325) sieve. Fineness can also be assessed by methods that estimate specific surface area, such as the Blaine air permeability test(7) commonly used for Portland cement.

Pozzolanic Activity (Chemical Composition and Mineralogy): Pozzolanic activity refers to the ability of the silica and alumina components of fly ash to react with available calcium and/or magnesium from the hydration products of Portland cement. ASTM C618 requires that the pozzolanic activity index with Portland cement, as determined in accordance with ASTM C311,(6) be a minimum of 75 percent of the average 28-day compressive strength of control mixes made with Portland cement.

Loss on Ignition: Many state transportation departments specify a maximum LOI value that does not exceed 3 or 4 percent, even though the ASTM criteria is a maximum LOI content of 6 percent.(2) This is because carbon contents (reflected by LOI) higher than 3 to 4 percent have an adverse effect on air entrainment.

Fly ashes must have a low enough LOI (usually less than 3.0 percent) to satisfy ready-mix concrete producers, who are concerned about product quality and the control of air-entraining admixtures. Furthermore, consistent LOI values are almost as important as low LOI values to ready-mix producers, who are most concerned with consistent and predictable quality.

Moisture Content: ASTM C618 specifies a maximum allowable moisture content of 3.0 percent.

Some of the properties of fly ash-concrete mixes that are of particular interest include mix workability, time of setting, bleeding, pumpability, strength development, heat of hydration, permeability, resistance to freeze-thaw, sulfate resistance, and alkali-silica reactivity.

Workability: At a given water-cement ratio, the spherical shape of most fly ash particles permits greater workability than with conventional concrete mixes. When fly ash is used, the absolute volume of cement plus fly ash usually exceeds that of cement in conventional concrete mixes. The increased ratio of solids volume to water volume produces a paste with improved plasticity and more cohesiveness.(8)

Time of Setting: When replacing up to 25 percent of the Portland cement in concrete, all Class F fly ashes and most Class C fly ashes increase the time of setting. However, some Class C fly ashes may have little effect on, or may possibly even decrease, the time of setting. Delays in setting time will probably be more pronounced, compared with conventional concrete mixes, during the cooler or colder months.(8)

Bleeding: Bleeding is usually reduced because of the greater volume of fines and lower required water content for a given degree of workability.(8)

Pumpability: Pumpability is increased by the same characteristics affecting workability, specifically, the lubricating effect of the spherical fly ash particles and the increased ratio of solids to liquid that makes the concrete less prone to segregation.(8)

Strength Development: Previous studies of fly ash concrete mixes have generally confirmed that most mixes that contain Class F fly ash that replaces Portland cement at a 1:1 (equal weight) ratio gain compressive strength, as well as tensile strength, more slowly than conventional concrete mixes for up to as long as 60 to 90 days. Beyond 60 to 90 days, Class F fly ash concrete mixes will ultimately exceed the strength of conventional PCC mixes.(5) For mixes with replacement ratios from 1.1 to 1.5:1 by weight of Class F fly ash to the Portland cement that is being replaced, 28-day strength development is approximately equal to that of conventional concrete.

Class C fly ashes often exhibit a higher rate of reaction at early ages than Class F fly ashes. Some Class C fly ashes are as effective as Portland cement in developing 28-day strength.(9) Both Class F and Class C fly ashes are beneficial in the production of high-strength concrete. The American Concrete Institute (ACI) recommends that Class F fly ash replace from 15 to 25 percent of the Portland cement and Class C fly ash replace from 20 to 35 percent.(10)

Heat of Hydration: The initial impetus for using fly ash in concrete stemmed from the fact that the more slowly reacting fly ash generates less heat per unit of time than the hydration of the faster reacting Portland cement. Thus, the temperature rise in large masses of concrete (such as dams) can be significantly reduced if fly ash is substituted for cement, since more of the heat can be dissipated as it develops. Not only is the risk of thermal cracking reduced, but greater ultimate strength is attained in concrete with fly ash because of the pozzolanic reaction.(8) Class F fly ashes are generally more effective than Class C fly ashes in reducing the heat of hydration.

Permeability: Fly ash reacting with available lime and alkalies generates additional cementitious compounds that act to block bleed channels, filling pore space and reducing the permeability of the hardened concrete.(5) The pozzolanic reaction consumes calcium hydroxide ($Ca(OH)_2$), which is leachable, replacing it with insoluble calcium silicate hydrates (CSH).(8) The increased volume of fines and reduced water content also play a role.

Resistance to Freeze-Thaw: As with all concretes, the resistance of fly ash concrete to damage from freezing and thawing depends on the adequacy of the air void system, as well as other factors, such as strength development, climate, and the use of deicer salts. Special attention must be given to attaining the proper amount of entrained air and air void distribution. Once fly ash concrete has developed adequate strength, no significant differences in concrete durability have usually been observed.(8) There should be no more tendency for fly ash concrete to scale in freezing and thawing exposures than conventional concrete, provided the fly ash concrete has achieved its design strength and has the proper air void system.

Sulfate Resistance: Class F fly ash will generally improve the sulfate resistance of any concrete mixture in which it is included.(11) Some Class C fly ashes may improve sulfate resistance, while others may actually reduce sulfate resistance(12) and accelerate deterioration.(13) Class C fly ashes should be individually tested before use in a sulfate environment. The relative resistance of fly ash to sulfate deterioration is reportedly a function of the ratio of calcium oxide to iron oxide.(12)

Alkali-Silica Reactivity: Class F fly ash has been effective in inhibiting or reducing expansive reactions resulting from the alkali-silica reaction. In theory, the reaction between the very small particles of amorphous silica glass in the fly ash and the alkalis in the Portland cement, as well as the fly ash, ties up the alkalis in a nonexpansive calcium-alkali-silica gel, preventing them from reacting with silica in aggregates, which can result in expansive reactions. However, because some fly ashes (including some Class C fly ashes) may have appreciable amounts of soluble alkalis, it is necessary to test materials to be used in the field to ensure that expansion due to alkali-silica reactivity will be reduced to safe levels.(8)

Fly ash, especially Class F fly ash, is effective in three ways in substantially reducing alkali-silica expansion: 1) it produces a denser, less permeable concrete; 2) when used as a cement replacement it reduces total alkali content by reducing the Portland cement; and 3) alkalis react with fly ash instead of reactive silica aggregates.(14) Class F fly ashes are probably more effective than Class C fly ashes because of their higher silica content, which can react with alkalis. Users of Class C fly ash are cautioned to carefully evaluate the long-term volume stability of concrete mixes in the laboratory prior to field use, with ASTM C441(15) as a suggested method of test.

DESIGN CONSIDERATIONS

Mix Design

Concrete mixes are designed by selecting the proportions of the mix components that will develop the required strength, produce a workable consistency concrete that can be handled and placed easily, attain sufficient durability under exposure to in-service environmental conditions, and be economical. Procedures for proportioning fly ash concrete mixes differ slightly from those for conventional concrete mixes. Basic mix design guidelines for normal concrete (16) and high-strength concrete are provided by ACI.(10)

One mix design approach commonly used in proportioning fly ash concrete mixes is to use a mix design with all Portland cement, remove some of the Portland cement, and then add fly ash to compensate for the cement that is removed. Class C fly ash is usually substituted at a 1:1 ratio. Class F fly ash may also be substituted at a 1:1 ratio, but is sometimes specified at a 1.25:1 ratio, and in some cases may even be substituted at a 1.5:1 ratio.(5) There are some states that require that fly ash be added in certain mixes with no reduction in cement content.

The percentage of Class F fly ash used as a percent of total cementitious material in typical highway pavement or structural concrete mixes usually ranges from 15 to 25 percent by weight.(5) This percentage usually ranges from 20 to 35 percent when Class C fly ash is used.(10)

Mix design procedures for normal, as well as high-strength, concrete involve a determination of the total weight of cementitious materials (cement plus fly ash) for each trial mixture that is being investigated in the laboratory. The ACI mix proportioning guidelines recommend a separate trial mix for each 5-percent increment in the replacement of Portland cement by fly ash. If fly ash is to replace Portland cement on an equal weight (1:1) basis, the total weight of cementitious material in each trial mix will remain the same. However, because of differences in the specific gravity values of Portland cement and fly ash, the volume of cementitious material will vary with each trial mixture.(10)

When a Type IP (Portland-pozzolan) or Type I-PM blended cement is used in a concrete mix, fly ash is already a part of the cementing material. There is no need to add more fly ash to a concrete mix in which blended cement is being used, and it is recommended that no fly ash be added in such cases. The blended cement can be used in the mix design process in essentially the same way as a Type I Portland cement.

To select a mix proportion that satisfies the design requirements for a particular project, trial mixes must be made. In a concrete mix design, the water-cement (w/c) ratio is a key design parameter, with a typical range being from 0.37 to 0.50. When using a blended cement, the water demand will probably be somewhat reduced because of the presence of the fly ash in the blended cement. When fly ash is used as a separately batched material, trial mixes should be made using a water-cement plus fly ash (w/c+f) ratio, sometimes referred to as the water-cementitious ratio, instead of the conventional w/c ratio.(16)

The design of any concrete mix, including fly ash concrete mixes, is based on proportioning the mix at varying water-cementitious ratios to meet or exceed requirements for compressive strength (at various ages), entrained air content, and slump or workability needs. The mix design procedures stipulated in ACI 211.1 provide detailed, step-by-step directions regarding trial mix proportioning of the water, cement (or cement plus fly ash), and aggregate materials. Fly ash has a lower specific gravity than Portland cement, which must be taken into consideration in the mix proportioning process.

Structural Design

Structural design procedures for concrete pavements containing fly ash are no different than design procedures for conventional concrete pavements. The procedures are based to a great extent on the design strength of the concrete mix, usually determined by testing after moist curing for 28 days. For structural concrete, the design strength is usually the unconfined compressive strength as determined by ASTM C39.(17) For pavement concrete, the design strength may be either the tensile or flexural strength, or possibly the unconfined compressive strength.

CONSTRUCTION PROCEDURES

Material Handling and Storage

When fly ash is used as a mineral admixture, the ready-mix producer typically handles fly ash in the same manner as Portland cement, except that fly ash must be stored in a separate silo from the Portland cement.

Mixing, Placing, and Compacting

Certain fly ashes will reduce the effectiveness of air entraining agents, requiring a higher dosage to meet specifications. Therefore, the concrete producer must ensure that the proper amount of air entraining admixture is added during mixing, so that the air content of the concrete is within specified limits. The air content of the concrete must be carefully checked and adjusted during production to ensure that it remains within those limits. As with any concrete, excessive vibration should be avoided because it may reduce the air content of the in-place concrete.(5)

Placement and handling of fly ash concrete is in most respects similar to that of normal concrete. Fly ash concrete using Class F fly ash has a slower setting time than normal concrete. As a result, finishing operations may have to be delayed, possibly by 1 to 2 hours, depending on the temperature. Also, fly ash concrete surfaces may tend to be more sticky than normal concrete during placement and finishing, although properly proportioned concrete mixes containing fly ash should benefit workability and finishing.(5) Normal procedures for screeding, finishing, edging, and jointing of conventional PCC are also applicable to fly ash concrete.

Curing

The slower strength development of concrete containing Class F fly ash may require that the moisture be retained in the concrete for a longer period of time than what is normally required for conventional concrete. The proper application of a curing compound should retain moisture in the concrete for a sufficient period of time to permit strength development. Normal curing practices should be adequate for concrete containing Class F fly ash.

Scheduling of pavement construction should allow adequate time for the desired or specified strength gain prior to the placement of traffic loads, the onset of freeze-thaw cycles, and the application of deicing salts because of the detrimental effect of cold weather on strength gain. Some states, such as Wisconsin, have a construction cut-off date beyond which fly ash is not permitted to be used in concrete until the following spring. There is less of a concern with the use of Class C fly ash in cold weather than Class F fly ash.

Rather than relying on a cut-off date, the percentage of fly ash could be reduced during colder weather, or other measures (such as additional Portland cement, or the possible use of high-early strength cement, or a chemical accelerator) could be taken to maintain or improve strength development under low temperature conditions. Normal construction practices for cold weather concreting (such as heated aggregates and mixing water, reducing the slump of the concrete, covering the poured concrete with insulation material, and using space heaters for inside pours) are also applicable for concrete containing some fly ash.(18)

Quality Control

The most important quality control consideration concerning the use of fly ash in PCC mixes is to ensure that the air content of the freshly mixed concrete is within specified limits and does not fluctuate to any greater extent than a normal PCC mix. To ensure that this is the case, air content testing of fly ash concrete mixes may initially need to be done at a greater frequency than with normal PCC mixes. Another important quality control consideration in freshly mixed PCC is its workability, as determined by performing slump tests. Slump testing of fly ash concrete can be done at the same frequency as for normal PCC mixes.

UNRESOLVED ISSUES

An improved means of classifying and specifying fly ash sources for use as a mineral admixture in PCC is needed.

There are considerable laboratory and limited field data that indicate that high percentage (50 to 70 percent) Class F or Class C fly ash, in combination with a high range water reducing admixture, produces concrete with exceptional compressive strength.(19) Trial usage of high percentage fly ash concrete mixes is needed in order to be able to evaluate the field performance of these mixes.

Class F fly ash may have cementitious ability when blended with other by-products such as cement kiln dust prior to being introduced into a concrete mix. Additional data are needed on the characteristics and long-term performance of concrete mixes in which a blend of fly ash and other cementitious (or pozzolanic) by-products is used.

As a consequence of the Clean Air Act, many coal-fired power plants are being equipped with low NO_x burners. The short-term effect of burning coal in a low NO_x burner appears to be an increase in the LOI of the fly ash. The coal ash industry is developing comparative information on the characteristics and engineering properties of ASTM C618 sources of fly ash before and after installation of low NO_x burners. Some fly ash sources do not have acceptable LOI values once low NO_x burners have been installed and put into operation.

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INTRODUCTION

Coal fly ash has been successfully used as a structural fill or embankment material for highway construction projects in a number of different locations throughout the United States. Compared with conventional soils used to build embankments, fly ash is somewhat of a unique engineering material. When dry, fly ash is cohesionless and considered by many as a dusty nuisance. When saturated, fly ash becomes an unmanageable mess. But, as with most fine-grained soils, fly ash can be easily handled and compacted at more intermediate moisture contents, and does exhibit some cohesion.

Nearly all of the fly ash used for embankment construction is anthracite or bituminous coal fly ash. Lignite or subbituminous fly ashes, which are usually self-cementing, can harden prematurely when moisture is added, resulting in potential handling problems and inability to achieve the required degree of compaction. Fly ash use as a structural fill or embankment material was pioneered during the 1950's in Great Britain, where it is still bid as an alternate borrow material on roadway fill projects in areas where it is available.

PERFORMANCE RECORD

It has been reported that since 1970 at least 14 states have used fly ash to construct or repair embankments.(1) Fly ash has also been used as a structural backfill material behind retaining walls and bridge abutments. States that have thus far used fly ash as an embankment or structural backfill material include Arizona, Delaware, Illinois, Maryland, Massachusetts, Michigan, Minnesota, Missouri, Ohio, Oklahoma, Pennsylvania, Virginia, West Virginia, and Wisconsin. At least nine states have a specification for the use of fly ash as an embankment material.(1)

Table 5-4 provides a list of the number, estimated size, location, and year of construction of the known fly ash embankment or structural backfill projects that have been built in each of these states. This list, which may not be complete, encompasses at least 21 highway construction projects,(2) involving an estimated 2 million or more cubic yards of fly ash, in some cases mixed with bottom ash.

Although very few of these projects have been monitored for long-term performance, none of the states in which these projects have been constructed have indicated any dissatisfaction or concern with the embankments or backfills constructed using fly ash in their states. Two of the ash embankment projects listed in Table 5-4 (one in Delaware and one in Pennsylvania) were monitored for construction and postconstruction performance over a 3-year time period.(3,4) The monitoring consisted of sampling and analyzing ash physical and engineering characteristics, evaluating ash placement and compaction behavior, collecting and analyzing samples from groundwater monitoring wells, and periodically taking settlement readings from selected locations within each embankment. Neither of these two projects showed any signs of undue settlement or adverse environmental impacts over the 3-year monitoring period.

Table 5-4. List of fly ash embankment or structural backfill projects constructed in the United States.

State	No. of Projects	Year Built	Project Location	Estimated Tonnage or Volume
Arizona	1	1980	I-40, Joseph City	47,600 m^3 (61,000 yd^3)
Delaware	2	1987 1992	I-495, Wilmington Route 1, Dover	6,300 m^3 (8,300 yd^3) 237,000 T (262,000 t)
Illinois	1	1972	Waukegan	190,000 m^3 (246,000 yd^3)
Maryland	1	1993	Rt. 213, Easton	91,000 T (100,000 t)
Massachusetts	1	1978	Norton	3,800 m^3 (5,000 yd^3)
Michigan	1	1978	Railroad Bridge, Monroe	2,030 m^3 (2,650 yd^3)
Minnesota	2	1971 1978	St. Paul Rt. 13, Eagan	38,000 m^3 (50,000 yd^3) 270,000 m^3 (350,000 yd^3)
Missouri	1	1983	ASB Bridge, Kansas City	107,000 m^3 (140,000 yd^3)
Ohio	3	1979 1981 1983	Rt. 7, Powhatan Point I-480, Avon Rt. 35, Gallia Co.	5,200 T (5,700 t) 27,000 T (30,000 t) 24,000 T (27,000 t)
Oklahoma	1	1982	US 62, Muskogee	450 T (500 t)
Pennsylvania	2	1977 1988	Culver Rd., Pittsburgh I-279, Pittsburgh	57,000 m^3 (75,000 yd^3) 321,000 T (353,000 t)
Virginia	1	1978	Rt. 665, Carbo	270 T (300 t)
West Virginia	2	1971 1976	Rt. 250, Fairmont Rt. 60/12, Malden	4,500 T (5,000 t) 15,300 m^3 (20,000 yd^3)
Wisconsin	At least 4	1977 1978-90	Airport Spur, Milwaukee Various Projects	109,000 T (120,000 t) 270,000 T (300,000 t)

When used in structural fills or embankments, fly ash offers several advantages over natural soil or rock. Its relatively low unit weight makes it well suited for placement over soft or low bearing strength soils, and its high shear strength, compared with its unit weight, results in good bearing support and minimal settlement. The ease with which fly ash can be placed and compacted, especially when placed at the proper moisture content, can reduce construction time and equipment costs. In areas where fly ash is readily available in bulk quantities, costs for the purchase, permitting, and operation of a borrow pit can be reduced or eliminated.(5)

There are some disadvantages of using fly ash in structural fills or embankments. Unless delivered to the project site within the proper moisture range, dust control measures may be needed. Also, since fly ash is a predominantly silt-size material, it is subject to erosion and, as a result, erosion control procedures may be needed.

MATERIAL PROCESSING REQUIREMENTS

Moisture Control

The only property or characteristic of fly ash that may need to be adjusted or modified before delivery of the ash to the job site is its moisture content. The optimum moisture content of the fly ash to be used must be determined well in advance of starting the project. To achieve the desired degree of compaction in the field, the fly ash being supplied to the job must be delivered to the site as close to its optimum moisture content as possible.

Although specification requirements may vary somewhat from job to job, fly ash for embankment construction should usually be delivered to the job site within 3 to 4 percent of its optimum moisture content, preferably on the dry side of optimum.(3) Dry fly ash from a silo must be water conditioned to the desired moisture content. Conditioned fly ash from a landfill should be excavated from the landfill, stockpiled, and additional moisture added, if needed, prior to delivery. Ponded fly ash must be removed from a lagoon, stockpiled until the moisture content has been sufficiently reduced for placement, then delivered to the job site.

Since most lignite or subbituminous fly ashes are self-cementing, the addition of moisture in amounts approaching the optimum moisture content may result in flash setting or sudden hardening of the ash. To prepare this type of fly ash for use as embankment material, the ash may need to be lightly conditioned with water (10 to 15 percent), stockpiled for several weeks, and passed through a crusher to remove agglomerations prior to its use as fill. Additional water, if needed, should be added only after the lignite or subbituminous fly ash has been placed and just prior to compaction.

ENGINEERING PROPERTIES

Some of the engineering properties of fly ash that are of particular interest when fly ash is used as an embankment or fill material are its moisture-density relationship, particle size distribution, shear strength, consolidation characteristics, bearing strength, and permeability.

Moisture-Density Relationship: Fly ash has a relatively low compacted density, thereby reducing the applied loading and resultant settlement to the supporting subgrade. Conditioned fly ash tailgated over the slope of an embankment can have a loose dry density as low as 650 to 810 kg/m^3 (40 to 50 lb/ft^3). However, when it has been well-compacted at an optimum moisture content (usually between 20 and 35 percent), the dry unit weight of fly ash may be greater than 1380 kg/m^3 (85 lb/ft^3), possibly even as high as 1620 kg/m^3 (100 lb/ft^3).

Particle Size Distribution: Fly ash is predominantly a silt-sized nonplastic material. Between 60 and 90 percent of fly ash particles are finer than a 0.075 mm (No. 200) sieve. As such, its particle size distribution falls essentially within the normally recognized limits for frost-susceptible soils.(6) The potential for frost susceptibility of fly ash may account for the reluctance on the part of some geotechnical engineers to use fly ash as a fill material. The fine particle sizing of fly ash, together with the relative uniformity of the gradation in the coarse silt range, makes it imperative that the ash be handled with sufficient water to prevent dusting. Since fine-grained soils can be fairly easily eroded, enough moisture must also be present to support compaction equipment and to permit the material to be well-densified, in order to prevent or minimize erodibility.

Shear Strength: Shear strength tests conducted on freshly compacted fly ash samples show that fly ash derives most of its shear strength from internal friction, although some apparent cohesion has been observed in certain bituminous (pozzolanic) fly ashes.(7) The shear strength of fly ash is affected by the density and moisture content of the test sample, with maximum shear strength exhibited at the optimum moisture content.(8) Bituminous fly ash has been determined to have a friction angle that is usually in the range of 26° to 42°. A test program involving shear strength testing for 51 different ash samples resulted in a mean friction angle value of 34°, with a fairly wide range.(9)

Consolidation Characteristics: An embankment or structural backfill should possess low compressibility to minimize roadway settlements or differential settlements between structures and adjacent approaches. Consolidation has been shown to occur more rapidly in compacted fly ash than in silty clay soil because the fly ash has a higher void ratio and greater permeability than the soil. For fly ashes with age-hardening properties, including most "high lime" fly ashes from lignite or subbituminous coals, the age-hardening can reduce the time rate of consolidation, as well as the magnitude of the compressibility.

Bearing Strength: California bearing ratio (CBR) values for "low lime" fly ash from the burning of anthracite or bituminous coals have been found to range from 6.8 to 13.5 percent in the soaked condition (an optional procedure in the test method)(10) to 10.8 to 15.4 percent in the unsoaked condition.(11) For naturally occurring soils, CBR values normally range from 3 to 15 percent for fine-grained materials (silts and clays), from 10 to 40 percent for sand and sandy soils, and from 20 to 80 percent for gravels and gravelly soils.(12)

Permeability: The permeability of well-compacted fly ash has been found to range from 10^{-4} to 10^{-6} cm/s, which is roughly equivalent to the normal range of permeability of a silty sand to silty clay soil.(12) The permeability of a material is affected by its density or degree of compaction, its grain size distribution, and its internal pore structure. Since fly ash consists almost entirely of spherical shaped particles, the particles are able to be densely packed during compaction, resulting in comparatively low permeability values and minimizing seepage of water through a fly ash embankment.

DESIGN CONSIDERATIONS

Virtually any fly ash can be used as an embankment or structural backfill material, including ponded ash that has been reclaimed from an ash lagoon. The principal technical considerations related to the design of a fly ash embankment or structural backfill are essentially the same as the considerations for the design of an earthen embankment or backfill. There are certain special design considerations, however, that should be considered when fly ash is used in embankment or fill applications.

Site Drainage

Fly ash, because of its predominance of silt-size particles, tends to wick water into itself, making it possible that the lower extremities of a fly ash embankment could become saturated, resulting in a loss of shear strength. It is, therefore, important that the base of a fly ash embankment not be exposed to free moisture, wetlands, or the presence of a high water table condition. Adequate provisions should be made to handle maximum flows anticipated from surface waterways, swales, or seepage from springs or high water table conditions.

An effective way to prevent capillary rise or the effects of seepage in fly ash embankments and backfills is the placement of a drainage layer of well-drained granular material at the base of the embankment. An ASTM recommended practice for the use of fly ash in structural fills recommends placement of a drainage layer at a height that is at least 5 feet above the historical high water table.(13)

Slope Stability

To determine a safe and appropriate design slope ratio (the ratio of vertical to horizontal distance), an analysis of the slope stability of a design cross-section of the fly ash embankment must be performed. The basic principle of slope stability analysis is to compare the factors contributing to instability with those resisting failure. The principal resistance to failure is the shear strength of the embankment material. For long-term stability of fly ash embankments, a factor of safety (ratio of the resisting forces to the driving forces along a potential failure surface) of 1.5 is recommended using the Swedish circle method of slope stability analysis.(14) Unless the fly ash is self-hardening, the cohesion (c) value should be zero for these calculations.

Erosion Control Analysis

The slope ratio described above is also a factor in the potential for erodibility of compacted fly ash slopes. These slopes must be protected as soon as possible after attaining final grade because they are subject to severe erosion by runoff, or even high winds, if left unprotected. One way to prevent such erosion is to construct a fly ash embankment within dikes of granular soil, which serve to protect the slopes throughout construction. Another way is to cover the slopes with topsoil as the embankment is being constructed. It is also possible to overfill the slopes and trim the excess fly ash back to the appropriate slope once the final layer is completed. Finally, short-term erosion control may be accomplished by stabilizing the surface fly ash on the slopes with a low percentage of Portland cement or lime,(14) or covering with a blanket of coarse bottom ash.

Soil Bearing Capacity

The ability of the top portion of a fly ash embankment to support a pavement structure can be predicted by a determination of the California Bearing Ratio (CBR) for a flexible asphalt pavement system or by a determination of the modulus of subgrade reaction (K-value) for a rigid or concrete pavement system. These bearing values can then be used to design pavement layer thicknesses in accordance with the AASHTO Design Guide.(15)

Climatic Conditions

Although no frost susceptibility criteria have been established in the United States, the British Road Research Laboratory has developed a test method to evaluate frost susceptibility.(16) The test method involves subjecting a compacted 150 mm (6 in) high specimen to freezing temperatures that simulate actual field conditions. The test is run over a 250-hour time period, after which the total amount of frost heave of the test specimen is measured. Frost-susceptible materials heave 18 mm (0.7 in) or more after testing.

The resistance of the top portion of a fly ash embankment to frost heaving can be substantially increased by the addition of moderate amounts of cement or lime. Objections to the use of compacted fly ash within the frost depth can be overcome by substituting a soil that is not susceptible to frost for fly ash within the frost zone.

During times of heavy or prolonged precipitation, the delivered moisture content of the fly ash may have to be reduced to compensate for the effects of the precipitation. Fly ash, unlike most soils, can usually be compacted throughout much of the winter, although it is recommended that fly ash not be spread and compacted when the ambient air temperature is below -4 °C (25 °F).(14)

Protection of Underground Pipes and Adjacent Concrete

Chemical and/or electrical resistivity tests of some fly ashes have indicated that certain ash sources may be potentially corrosive to metal pipes placed within an embankment. Each source of fly ash should be individually evaluated for its corrosivity potential. If protection of metal pipes is deemed necessary, the exterior of the pipes may be coated with tar or asphalt cement, the pipes may be wrapped with polyethylene sheeting, or the pipes can be backfilled with sand or an inert material.(14)

The sulfate content of fly ash, particularly self-cementing ash, has caused some concern about the possibility of sulfate attack on adjacent concrete foundations or walls. Precautions that can be taken against potential sulfate attack of concrete include painting concrete faces with tar or an asphalt cement, using a waterproof membrane (such as polyethylene sheeting or tar paper), or possibly even using a Type V sulfate-resistant cement in the adjacent concrete.

CONSTRUCTION PROCEDURES

Material Handling and Storage

Bituminous (pozzolanic) fly ash is usually conditioned with water at the power plant and hauled in covered dump trucks with sealed tailgates. Subbituminous or lignite (self-cementing) fly ash may be partially conditioned at the plant and hauled in covered dump trucks to the project site, or hauled dry in pneumatic tank trucks from the plant to the project site, where it is placed in a silo and conditioned with water when ready for placement.

If a temporary stockpile of fly ash is built at the project site, the surface of the stockpile must be kept damp enough to prevent dusting. The stockpile should be placed in a well-drained area so the ash is not inundated with water following a rainfall.(14)

Placing and Compacting

The minimum amount of construction equipment needed to properly place and compact fly ash in an embankment or structural backfill includes a bulldozer for spreading the material, a compactor, either a vibrating or pneumatic tired roller, a water truck to provide water for compaction (if needed) and to control dusting, and a motor grader, where final grade control is critical.

The suitability of any proposed construction equipment should be verified by using it on a test strip prior to its use in actual construction. The test strip may also be used to evaluate the specified compaction procedure, as well as any proposed modifications to the procedure. If fly ash from a power plant's landfill or lagoon contains any lumps when spread for compaction, it may be necessary to break down the lumps using a disk harrow or a rotary tiller as a supplemental piece of equipment.(14)

Fly ash should be placed in uniform lifts no thicker than 0.3 m (12 in) when loose. Experience has shown that steel-wheel vibratory compactors and/or pneumatic tired rollers have provided the best performance. If a vibratory roller is used, the first pass should be made with the roller in the static mode (without any vibration), followed by two passes with the roller in the vibratory mode and traveling relatively fast. Additional passes should be in the vibratory mode at slow speed.(13)

In general, six passes of the roller are usually needed to meet specified compaction requirements. In most cases, 90 to 95 percent of a standard Proctor maximum dry density is the minimum specified density to be achieved. This is almost always achievable when the moisture content of the fly ash is within 2 or 3 percent of optimum, preferably on the dry side of optimum.(17)

For each project, the type of compactor, the moisture content of the fly ash at placement, the lift thickness, and the number of passes of the compaction equipment should be evaluated using a test strip before the actual construction. If a vibratory compactor is to be used, the test strip can be used to evaluate the speed at which the compactor should be operated, the static weight, dynamic force and frequency of vibration of the compactor, and the number of passes required to achieve the specified density.(14)

During periods of moderate rainfall, construction may proceed by reducing the amount of water added at the power plant or jobsite to compensate for precipitation. Dry fly ash can also be mixed into excessively wet fly ash to reduce the moisture content to an acceptable level.

Because fly ash obtained directly from silos or hoppers dissipates heat slowly, fly ash may be placed during cold weather. If frost does penetrate a few inches into the top surface of the fly ash, the ash can be removed from the surface by a bulldozer, or recompacted after thawing and drying.(13) Construction should be suspended during severe weather conditions, such as heavy rainfall, snowstorms, or prolonged and/or excessively cold temperatures.

Quality Control

Quality control programs for fly ash embankments or structural backfills are similar to such programs for conventional earthwork projects. These programs typically include visual observations of lift thickness, number of compactor passes per lift, and behavior of fly ash under the weight of the compaction equipment, supplemented by laboratory and field testing to confirm that the compacted fly ash has been constructed in accordance with design specifications.(13)

Special Considerations

Dust Control

If allowed to dry out, fly ash surfaces can be susceptible to dusting. Dust control measures that are routinely used on earthwork projects are effective in minimizing airborne particulates at ash fill projects. Typical controls include hauling fly ash in covered dump trucks (for "low lime") or in pneumatic tankers (for "high lime"), moisture conditioning fly ash at the power plant (especially "low lime"), wetting or covering exposed fly ash surfaces, and sealing the top surface of compacted fly ash by the compactor at the conclusion of each day's placement.(13)

Drainage/Erosion Protection

Fly ash surfaces must be graded or sloped at the end of each working day to provide positive drainage and prevent the ponding of water or the formation of runoff channels that could erode slopes and produce sediment in nearby surface waters. Compacted fly ash slopes must be protected as soon as possible after being finish graded because, if left unprotected, they can be severely eroded. Erosion control on side slopes is usually provided by placing from 150 mm (6 in) to 600 mm (2 ft) of soil cover on the slopes. An alternative approach is to build outside dikes of soil to contain the fly ash as the embankment is being constructed.(14)

UNRESOLVED ISSUES

Since coal fly ash consists of predominantly silt-sized particles, there is sometimes a concern about the possible frost susceptibility of fly ash as an embankment or structural backfill material, especially in northern climates. Normally, earthen materials that are primarily in the silt grain size range are frost susceptible. However, some fly ashes are frost susceptible while others are not. More testing of fly ashes needs to be done to determine why this is so and to develop a more accurate predictor for frost susceptibility.

Bituminous (pozzolanic) fly ash is more frequently used to construct embankments and structural backfills than subbituminous or lignite (self-cementing) fly ash. This is due in part to the self-cementing characteristics of the latter type, which hardens almost immediately after the addition of water. Current practice is to lightly condition self-cementing fly ashes with water, allow them to stockpile for a period of time, then run the partially hardened fly ash through a primary crusher before taking it to the project site. There is a need to develop more well-defined handling and preconditioning procedures for using self-cementing fly ash as a fill material.

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INTRODUCTION

Fly ash is often used as a component of stabilized base and subbase mixtures. Both bituminous (pozzolanic) and subbituminous or lignite (self-cementing) fly ashes can be used in this application.

Bituminous fly ash is used with a chemical reagent or activator (usually lime, Portland cement, or kiln dust), aggregate, and water. For most coarse graded aggregates, the amount of fly ash used will normally be in the 8 to 20 percent range. For sandy aggregates, the amount of fly ash used may be in the 15 to 30 percent range.

Subbituminous or lignite fly ash, which is usually self-cementing, does not require a chemical reagent or activator. This ash is blended with aggregate and water, but, because of the flash setting properties of most sources, the amount of fly ash used may only be in the 5 to 15 percent range. There are instances where self-cementing fly ash is used by itself as the base course material without any aggregate.

The use of fly ash in stabilized base and subbase mixtures dates back to the 1950's, when a patented base course product known as Poz-o-Pac (consisting of a blend of lime, fly ash, and aggregate) was originally developed. Since the Poz-o-Pac patents expired during the early 1970's, numerous variations of the basic lime-fly ash-aggregate formulations have evolved. There have also been stabilized base mixtures containing Portland cement that have evolved from soil-cement. All of these mixtures contain fly ash and can be described under the general heading of pozzolan-stabilized base (PSB).

The major component of most stabilized base mixtures is the aggregate. Early Poz-o-Pac mixes used locally available high-quality crushed rock (such as limestone, trap rock, or granite), sand and gravel, or blast furnace slag, especially on high traffic volume roadways. However, many well-constructed PSB mixes have been placed within haul roads, residential streets, and local roadways using power plant aggregates (bottom ash or boiler slag), marginal aggregates (including some off-spec materials), coal refuse, and reclaimed paving materials. Such alternative aggregates are often available and economical in areas where high-quality aggregate materials may be in short supply.

PERFORMANCE RECORD

The successful performance of PSB mixtures depends on the development of strength within the cementitious matrix formed by the pozzolanic reaction between the fly ash and the activator. This cementitious matrix acts as a binder that holds the aggregate particles together, similar in many respects to a low-strength concrete. However, unlike concrete, PSB mixtures are produced at a compactable consistency, not a plastic consistency, for placement at or near optimum moisture content and densification by roller compaction.

According to a 1992 survey of state transportation agencies, at least 22 states have made some use of fly ash in stabilized base or subbase applications.(1) Table 5-5 is a summary of the use of fly ash in stabilized base mixtures in these states.

Table 5-5. Summary of fly ash use in stabilized base and subbase applications throughout the United States.

State	Estimated Number of Projects	Time Period	Types of Projects	Remarks**
Alabama	Unknown	1955-1965	State roads	Used Class F fly ash
Arkansas*	At least 1	1982	State road	Test section w/100% Class C
Colorado	Unknown	Mid to late 1980's	Local roads	Used in Aurora, Denver suburb
Georgia	At least 1	1985	State road	EPRI fly ash demonstration
Illinois	Over 100	1955-1985	State/county roads	Class F & C ashes (Cook Cty)
Iowa	At least 1	Early to mid 1960's	County road	Class F ash used in Linn Cty
Kansas	At least 3	1987	County roads	EPRI fly ash demonstration
Kentucky*	At least 1	1984	State road	Used kiln dust and Class F ash
Maryland	At least 1	Early 1960's	Shoulders	Used for I-94 shoulders
Michigan*	At least 3	1959-1987	State/private roads	EPRI fly ash demonstration
Mississippi*	Unknown	1983	State road	Used Class C fly ash
Missouri	At least 10	1970-1988	State/local roads	Class F ash used in Kansas City
Nebraska	At least 1	Unknown	State road	Used Class C ash in subbase
New Jersey*	At least 1	1984	State road	Used on portion of I-295
North Dakota	Several	1971 to mid 1980's	State road	Used lignite ash at I-94
Ohio	At least 10	1970-1995	State/local roads	Used mainly in Toledo
Oklahoma	At least 1	Early to mid 1980's	State road	Used Class C fly ash
Pennsylvania	Several dozen	1954-1985	State/local roads	Used mainly in S.E. PA
Tennessee*	At least 1	1982	State road	Used Class F fly ash
Texas	Unknown	1960-1990	State/local roads	Used Class C and Class F ash
Virginia*	At least 1	1982	State road	Dulles Airport extension road
Wyoming	Unknown	Early to mid 1980's	State roads	Used Class C fly ash

*Participated in Federal Highway Administration (FHWA) Demonstration Program No. 59, "Fly Ash in Highway Construction."

**Note: Class F fly ash refers to the fly ash derived from the burning of bituminous coals. Class C fly ash refers to the fly ash derived from the burning of either lignite or subbituminous coals.

The three states in which PSB mixtures have been most frequently used are Illinois, Ohio, and Pennsylvania. It has been conservatively estimated that since the 1970's at least 25 to 30 million tons of PSB material have been produced and placed in the United States. One-third to one-half of all the PSB material placed prior to 1990 is thought to have been placed in the metropolitan Chicago area.(2)

Many of the stabilized base and subbase installations have been placed in low traffic areas such as local streets or parking lots. These installations have not usually been well documented. There are, however, a number of PSB projects that have been well reported and have provided excellent performance. At least seven states installed PSB base courses as part of Federal Highway Administration Demonstration Project No. 59, Fly Ash Use in Highway Construction, during the mid 1980's. Nearly all of these projects have been documented in terms of design and installation, although in many cases, long-term performance data is not available.

During the mid to late 1980's, the Electric Power Research Institute (EPRI) funded three demonstration projects in Georgia, Kansas, and Michigan that involved the use of fly ash in stabilized road base compositions. For each project, EPRI contracted with the utility company supplying the ash to determine basic material properties, assess construction performance, and evaluate long-term pavement and environmental performance for 3 years.

In 1985, the Georgia Department of Transportation constructed a 2.6 km (1.6 mi) relocation of State Route 22 west of Crawfordville. A portion of the two-lane road included a 305 m (1,000 ft) section of cement-stabilized pond ash base and a 244 m (800 ft) section of cement-stabilized fly ash base. Each of these two base course sections was 215 mm (8 1/2 in) thick. One year after installation, the average strength of the pond ash section was 14,570 kPa (2,115 lb/in^2) and the average strength of the fly ash section was 5,990 kPa (870 lb/in^2).(3)

During 1987, three county gravel roads in Kansas were recycled in place using Class C fly ash. At each site, the existing road surface was pulverized, mixed, and redeposited in its original location. Fly ash was spread over the pulverized road material and mixed by a means of a pulvi-mixer. Following compaction, a seal coat surface was placed on all three of the roadways. Since the reconstruction of these first three locations, more than 44 km (400 mi) of pavement recycling using Class C fly ash have been accomplished in Kansas and Oklahoma.(4)

Also in 1987, the shoulders of a 460 m (1,500 ft) long section of relocated Michigan Route M-54 near Flint were constructed using 620 metric tons (690 tons) of a cement-stabilized high carbon Class F fly ash base. A total of 915 m (3,000 ft) of shoulder material was placed at a width of 2.7 m (9 ft) and a compacted thickness of 250 mm (10 in). Core strengths after 270 days were variable, but reached as high as 6,890 kPa (1,000 lb/in^2). Although performance has been acceptable, some isolated areas of cracking were observed in both directions of the shoulder pavement after the first year of service.(5)

The largest single reported project in the United States involving the use of fly ash in PSB construction occurred during the early to mid 1970's with the building of runways, taxiways, and aprons at Newark International Airport, in Newark, New Jersey. A flexible pavement system using a base of lime, Portland cement, fly ash, and sand was designed to withstand the stresses from jumbo jet aircraft. The base course consisted of three layers, each with slight variations in the mix design. The lime and Portland cement combined ranged from 3 to 4 percent and the fly ash ranged from 10 to 12 percent. The PSB sections ranged in thickness from 610 to 914 mm (24 to 36 in). The ultimate strength of the 4 percent lime and Portland cement mix, which contains a blend of crushed stone and sand as the aggregate, was found to range from 13,780 to 17,910 kPa (2,000 to 2,600 lb/in^2).(6) After 20 or more years, the PSB pavements continue to perform satisfactorily.

PSB pavements have provided good to excellent performance over many years in numerous locations. In general, these mixtures have also been more economical than alternative base materials in many areas. Nonetheless, the major concern of highway engineers with stabilized base materials, including soil-cement, is the development of cracks within the base course. These cracks, which are more often caused by shrinkage rather than fatigue, usually reflect up through the overlying asphalt pavement surface, resulting in increased long-term maintenance costs.

MATERIAL PROCESSING REQUIREMENTS

Moisture Control

Aside from possible adjustments to moisture content, there is little to no processing required for using fly ash in PSB mixtures. For Class F fly ash, the moisture content is dictated by the type of equipment to be used in producing the base course material. If a central-mix concrete plant is used, the fly ash will most likely be fed from a silo in dry form. If a pugmill mixing plant is used, the fly ash will probably be fed from a storage bin in conditioned form. If PSB materials are to be mixed in place at the jobsite, Class F fly ash would also be placed and mixed in a conditioned form. Conditioned ash contains a minimal amount of water (usually 10 to 15 percent) to prevent dusting.

Activators (e.g., lime, Portland cement, kiln dust) are nearly always added to the mixture in a dry form. This means that the activators require no processing and will be delivered to the job site and stored in silos or tankers.

If Class C fly ash is used, it is likely to be self-cementing. For self-cementing fly ashes, there are two ways to offset the rapid hardening of base materials using such ashes. One is to initially condition the ash with relatively low amounts (in the range of 10 to 15 percent) of water, stockpile the partially hardened material for several weeks or more, then run the ash through a crusher to break down any agglomerations prior to use. The second is to use a commercial retarder (such as gypsum or borax) blended at a low percentage with the fly ash as a means of delaying the initial set.(7)

The aggregate(s) used in PSB mixtures should be in a saturated surface-dry condition during stockpiling. The moisture content of the aggregate(s) should be checked prior to mixing to ensure that excess moisture was not acquired while the aggregate(s) was being stockpiled.

ENGINEERING PROPERTIES

Some of the properties of fly ash that are of particular interest when fly ash is used in stabilized base applications include water solubility, moisture content, pozzolanic activity, fineness, and organic content.

Water Solubility: The physical requirements most frequently cited for the use of fly ash in PSB mixtures are provided in ASTM C593,(8) which specifies a maximum water soluble fraction of 10 percent.

Moisture Content: If conditioned fly ash is to be used, the moisture content of the conditioned ash must be determined prior to mixing in order to confirm that the moisture content is in the same range as the ash used for the mix design.

Pozzolanic Activity: One of the most important properties of fly ash, related to its use in PSB mixtures, is pozzolanic activity or reactivity. The pozzolanic reactivity is an indicator of the ability of a given source of fly ash to combine with calcium to form cementitious compounds. The pozzolanic reactivity of fly ash is influenced by its fineness, silica and alumina content, loss on ignition, and alkali content. Besides the gradation of the aggregate used, the pozzolanic reactivity of the fly ash is the major contributor to the strength of the base mix. Pozzolanic activity of fly ash with either lime or Portland cement can be determined using the test methods described in ASTM C311.(9)

Fineness: Fineness requirements in ASTM C593 specify that 98 percent of the fly ash should be finer than a 0.6 mm (No. 30) sieve and 70 percent finer than a 0.075 mm (No. 200) sieve. Most fly ash is capable of meeting these specifications. Minimum compressive strength requirements when fly ash is blended with lime at 7 and 21 days are also recommended in ASTM C593.(8)

Organic Content: Fly ash used in PSB mixtures does not have to meet the ASTM C618(10) requirements of fly ash that is used in Portland cement concrete. LOI is not a criterion for fly ash use in PSB mixtures.

Some of the properties of stabilized base mixes that are of particular interest when fly ash is incorporated include compressive strength, flexural strength, modulus of elasticity, bearing strength, autogeneous healing, fatigue, freeze-thaw durability, and permeability.

Compressive Strength: This is the most widely used criterion for the acceptability of PSB materials. Compressive strength testing of PSB mixtures is usually performed on Proctor-size specimens 10.2 cm (4 in) in diameter by 11.7 cm (4.6 in) in height, molded at or very close to the optimum moisture content of the mixture. Within limits, the higher the compressive strength, the better the quality of the stabilized material. For cement-stabilized base mixtures, the Portland Cement Association recommends a minimum 7-day compressive strength after curing at 23 °C (73 °F) of 3,100 kPa (450 lb/in^2).(11) Where lime or kiln dust is used as the activator, ASTM C593 specifies a minimum compressive strength, after 7 days of curing at 38 °C (100 °F), as 2,760 kPa (400 lb/in^2). The ultimate strength of PSB mixtures containing pozzolanic fly ash is considerably higher than the 7-day strength. In many cases, long term compressive strength development of pozzolanic fly ash mixes may be two to three times higher than the 7-day strength.

Actual compressive strength development of PSB mixtures in the field is time- and temperature-dependent. As the temperature increases, the rate of strength gain also increases. At or below 4 °C (40 °F), the pozzolanic reaction virtually ceases and the mixture no longer gains strength. However, once temperatures exceed 4 °C (40 °F), the pozzolanic reaction resumes and further strength gains occur. In this way, PSB mixtures continue to show incremental gains in strength over many years.

Flexural Strength: Because hardened PSB material is a semi-rigid pavement layer, the flexural strength of PSB mixtures may be a better indicator of the effective strength of this material. Although flexural strength can be determined directly by testing, most transportation agencies estimate the flexural strength of these materials as a fraction of the material's compressive strength. An average value of 20 percent of the unconfined compressive strength is considered to be a fairly accurate estimate of the flexural strength of PSB mixtures.(12)

Modulus of Elasticity: The modulus of elasticity is a measure of the stiffness or bending resistance of a material. For semi-rigid materials such as PSB mixtures, the relationship between stress and strain is not linear and, therefore, the modulus of elasticity is not a constant value, but increases as the compressive strength of the material increases. The modulus of elasticity, as determined from flexural strength testing instead of compressive strength testing, is recommended for use in pavement design calculations. For most PSB mixtures, the modulus of elasticity is in the range of 9.6 x 10^6 kPa (1.4 × 10^6 lb/in^2) to 17.2 x 10^6 kPa (2.5 × 10^6 lb/in^2).(13)

Bearing Strength: The California Bearing Ratio (CBR) test(14) is often used as a way of measuring the bearing strength of soils used as subgrade materials for highway and airfield pavements. Due to the relatively high strength of compacted PSB mixtures, high CBR values (in excess of 100 percent) are not that unusual. Use of the CBR test is more applicable to subgrade soil stabilization with fly ash than in evaluating PSB mixtures.

Autogenous Healing: One of the unique characteristics of PSB compositions is their inherent ability to heal or re-cement cracks within the material by means of a self-activating mechanism. This mechanism is referred to as autogenous healing and it results from the continuation of the pozzolanic reaction between the activator and the fly ash in the PSB mixture. The extent to which autogenous healing occurs depends on the age of the pavement when cracking develops, the degree of contact of the fractured surfaces, curing conditions, the strength of the pozzolanic reaction, and available moisture.(12)

Fatigue Properties: All engineering materials are subject to potential failure caused by progressive fracture under the action of repeated wheel loadings. In pavement design analysis, the flexural fatigue properties of PSB materials are a very important consideration. The flexural strength of PSB mixtures, like the compressive strength, increases with time, while the stress level (the ratio of applied stress to the modulus of rupture) gradually decreases. Because of autogenous healing, PSB mixtures are even less susceptible to fatigue failure than other conventional paving materials.(15)

Freeze-Thaw Durability: Durability testing of PSB materials is performed using one of two established test procedures. For lime and lime-based activators (including kiln dusts), the durability test procedure specified in ASTM C593 is used. This is a vacuum saturation procedure that has been correlated to weight loss after 12 freeze-thaw cycles. The acceptance criterion for ASTM C593 durability testing is that test specimens must have at least 400 psi unconfined compressive strength following vacuum saturation testing. For cement-based activators, the durability test procedure specified in ASTM D560(16) is used. The acceptance criterion is a maximum 14 percent weight loss after 12 freeze-thaw cycles.(16)

The minimum strength required prior to the first freezing cycle, in order to provide sufficient durability against freeze-thaw damage, is dependent on the severity of the climate. The American Coal Ash Association (ACAA) recommends the minimum compressive strengths of 6,900, 5,500 and 4,100 kPa (1000, 800, and 600 lb/in^2), respectively, for severe, moderate, and mild freeze-thaw conditions.(7)

Permeability: The permeability of hardened PSB materials is very low, depending on aggregate gradation, particularly when compared with that of crushed stone or granular bases and subbases, or even with the permeability of asphaltic base courses. In most cases, as the compressive strength of the PSB material increases, the permeability decreases. Initial permeability readings for hardened PSB mixtures can be expected to range between 10^{-5} and 10^{-6} cm/sec, as measured by the falling head permeability test. As the pozzolanic reaction proceeds, PSB materials may have permeability values between 10^{-6} and 10^{-7} cm/sec.(15)

DESIGN CONSIDERATIONS

Mix Design

A wide range of aggregate sizes can be accommodated in stabilized base and subbase mixtures. After determining the particle size distribution of the aggregate to be used in the PSB mixture, the initial step in determining the mix proportions is to find the optimum fines content. This is done by progressively increasing the quantity of fines (consisting of fly ash plus activator) and making density determinations for the blends of aggregate and fines. An estimated optimum moisture content is selected "by eye" and held constant for each blend. Each blend of aggregate and fines is compacted into a Proctor mold using standard compaction procedures. At least three such blends are required and five blends are recommended. Dry density versus fines content is plotted and this procedure is used to identify the percentage of fines (expressed as a percentage by dry weight of the total mixture) that results in the highest compacted dry density.

It is recommended that the optimum fines content selected by this procedure be 2 percent higher than the fines content at the maximum dry density. The optimum moisture content must then be determined for the mix design proportions selected by this procedure.

Once the fines content and optimum moisture have been determined, the ratio of activator to fly ash must also be determined. Using a series of trial mixtures, final mix proportions are selected on the basis of the results of both strength and durability testing according to ASTM C593 procedures.(8)

To determine the most suitable proportion of activator to fly ash, five different mix combinations should be evaluated at the optimum moisture content. The typical range of activator to fly ash ratios is 1:3 to 1:5 when using lime or Portland cement. The typical range of kiln dust to fly ash ratios is likely to be in the 1:1 to 1:2 range.

The ratio of fines (activator plus fly ash) to aggregate determines the amount of matrix available to fill the void spaces between aggregate particles. Normally, activator plus fly ash contents range from 12 to 30 percent by dry weight of the total mix, although fine-graded aggregates require a higher percentage for satisfactory strength development than well-graded aggregates.

In general, the trial mixture with the lowest ratio of activator to fly ash that satisfies both the strength and durability criteria is considered the most economical mixture. To ensure an adequate factor of safety for field placement, it is recommended that the PSB mixture used in the field have an activator content that is at least 0.5 percent higher (1.0 percent higher if kiln dust) than that of the most economical mixture identified in the laboratory tests.(7)

Structural Design

The design of pavements using PSB mixtures can be undertaken using AASHTO structural equivalency design methods.(17) The main factors influencing the variation in the structural layer coefficient for thickness design using the AASHTO method are the compressive strength and modulus of elasticity of the PSB material. The value of compressive strength most often used to determine the structural layer coefficient for PSB mixtures is the field design compressive strength. The field design compressive strength is simulated by the compressive strength determined in the laboratory after 56 days of moist curing at 23 °C (73 °F).(7) Other curing conditions may be required by various specifying agencies.

Based on the comparative performance of pozzolanic and crushed stone base materials from studies performed at the University of Illinois,(15) and using a value for a_1 of 0.44 (representing a bituminous concrete wearing surface) and a value for a_3 of 0.15 (representing a crushed stone base), structural layer coefficients for PSB mixtures were recommended. Table 5-6 provides a listing of recommended coefficients based on the early strength development of the mixtures.

Structural layer coefficient values (a_2) of 0.30 to 0.35 have been recommended for bituminous or Portland cement stabilized bases.(17)

CONSTRUCTION PROCEDURES

Material Handling and Storage

If the fly ash to be used in a PSB mixture is to be mixed in a dry form, the fly ash must be stored in a silo or pneumatic tanker until it is ready for use. If conditioned fly ash (usually Class F fly ash) is to be used, then the conditioned fly ash can be stockpiled until it is ready to be used. If fly ash is stockpiled for an extended period in dry or windy weather conditions, the stockpile may need to periodically be moistened to prevent unwanted dusting.

Table 5-6. Recommended structural coefficients for PSB mixtures.

Quality	Compressive Strength, kPa (lb/in^2) (7 days @ 38°C (100°F)	Recommended Structural Coefficient
High	Greater than 6,900 (1,000)	$a_2 = 0.34$
Average	4,500 to 6,900 (650 to 1,000)	$a_2 = 0.28$
Low	2,800 to 4,500 (400 to 650)	$a_2 = 0.20$

Mixing, Placing, and Compacting

The blending or mixing of PSB materials can be accomplished either in a mixing plant or in place. Plant mixing is recommended because it provides greater control over the quantities of materials batched, and it also results in the production of a more uniform PSB mixture.

Blending of PSB ingredients in a mixing plant can occur in discrete batches or by continuous mixing. Pugmill mixing plants blend accurately controlled amounts of aggregate, fly ash, activator, and water in batches in a mixing chamber, usually for periods of 30 to 45 seconds. Pugmill mixing plants can also be used with properly calibrated field conveyors from bins or silos for a continuous mixing operation. Rotating drum mixers have also been successfully used for blending PSB materials in batches.(13)

An alternative to plant mixing is in-place mixing. Although the mix-in-place approach does not usually result in as accurate a proportioning of the mix components as plant mixing, it is still possible to produce a high-quality PSB material using this approach. The various components of the PSB mixture are delivered and spread on the road site, then mixed in place using a pulvi-mixer, a self-propelled rotating device with mixing pads capable of mixing to a depth of 300 to 450 mm (12 to 18 in).

Plant-mixed materials should not be stockpiled, but should be delivered to the job site as soon as possible after mixing. Compaction of PSB materials should be completed as quickly as possible after placement, especially with mixtures containing self-cementing fly ash.

The delivery of PSB materials to the job site has been most frequently handled by covered end-dump hauling vehicles. The same equipment is basically used for spreading plant-mixed PSB material, as well as material to be mixed in place. Once the PSB material is dumped, spreading is usually accomplished by a bulldozer or a motor grader. However, plant-mixed material can also be spread to a more uniform and accurate loose thickness by a spreader box or a paving machine. The material must be as close as possible to optimum moisture content when placed.

During the in-place mixing operation, fly ash should be placed on the roadway first, either directly on a prepared subgrade, or above a layer of aggregate, if the PSB mixture contains aggregate. Fly ash is usually applied in a conditioned form to minimize dusting. The activator is then placed on top of the fly ash, usually in a dry condition, although lime has also been applied in a slurry form. The materials are then mixed together by means of a rotary mixer. Water is added as needed using a water truck with spray nozzles.

Equipment used for compaction is the same, regardless of whether PSB material is plant-mixed or mixed in place. For granular or more coarsely graded PSB materials, compaction requires the use of steel-wheeled, vibratory, or pneumatic rollers. For more fine-grained PSB materials, initial compaction often requires the use of a sheepsfoot roller, followed by a pneumatic roller.(7)

PSB materials should not be placed in layers that are less than 100 mm (4 in) or greater than 200 to 225 mm (8 to 9 in) in compacted thickness. The material should be spread in loose layers that are approximately 50 mm (2 in) greater in thickness prior to compaction than the desired compacted thickness. The top surface of an underlying layer should be scarified prior to placing the next layer.

Curing

After placing and compacting the PSB material, it must be properly cured to protect against drying and to assist in the development of in-place strength. If an asphalt concrete pavement is to be placed as an overlay, an asphalt emulsion seal coat should be applied to the top surface of the base or subbase within 24 hours of placement. The exact type of emulsion, rate of application, and temperature of the asphalt must be in compliance with applicable specifications.

The performance of pavement systems incorporating PSB material is dependent on the development of in-place strength following placement, compaction, and curing. Depending on the anticipated traffic loadings, it is necessary to analyze when traffic can be permitted to travel on the base material, while also avoiding potential fatigue damage due to early overloading.

Based on laboratory testing for strength development, it is usually possible to determine when the PSB material is likely to achieve an in-place compressive strength of 2,410 kPa (350 lb/in^2). Unless an asphalt surface or binder course has been placed over the PSB material, vehicles should not be permitted to use the PSB layer until it has achieved at least 2,410 kPa (350 lb/in^2)

in place. Ordinarily, placement of asphalt paving over the PSB material is recommended within 7 days after the PSB material has been placed.(7) If a Portland cement concrete pavement is to be constructed over the PSB layer, a waiting period of 7 days is also recommended.

Special Considerations

Late Season Construction

Unless pozzolan-stabilized materials are able to develop a certain level of strength prior to the first freeze-thaw cycle, these materials may be unable to withstand repeated freezing and thawing. Since strength development is time- and temperature-dependent, PSB material placed when the air temperature is too cold may not be able to develop the strength and durability needed for adequate freeze-thaw resistance. Normally, very little strength development occurs when the temperature within the PSB material is 5°C (40°F) or lower.

For northern states, state transportation agencies have previously established construction cutoff dates for PSB materials that range from September 15 to October 15, depending on location within state and/or ability to develop compressive strength in the laboratory.(18)

Self-Cementing Fly Ash

Self-cementing fly ash mixed with water alone usually results in a very rapid time of set. Delays between placement and compacting of PSB material containing self-cementing fly ash are accompanied by a significant decrease in the strength of the compacted base material, unless a retarder is used. Accordingly, PSB mixtures containing self-cementing fly ash should be compacted as soon as possible after mixing, with a recommended maximum elapsed time of no more than 2 hours between mixing and completion of compaction.(19)

Low percentages of water in the range of 10 to 25 percent by weight of ash, sufficient to retard dusting, can be added at the mixing plant, with added water that is required for proper compaction applied to the PSB material in place at the construction site before compaction.

A commercial retarder (such as gypsum, borax, or concrete retarding admixture) may be added in low percentages to the PSB material at the mixing plant. It has been found that the addition of 1 percent gypsum did not adversely affect the overall strength development of PSB material, but was effective in retarding rapid setting.(19,20)

Crack Control

Pavement base layers constructed with PSB materials are subject to shrinkage cracking. The development of cracks is related to the hydration reaction between the activator and fly ash and is more evident when Portland cement is used in the mix. Some cracks do reflect up through the overlying asphalt pavement, but are less likely to do so if a concrete pavement is used. If surface cracks are sealed to prevent the intrusion of water and subsequent damage due to freezing and thawing, the overall durability of the PSB layer should not be adversely affected.

Approaches for controlling or minimizing the potential effects of reflective cracking associated with PSB layers have been recommended by the ACAA.(7)

UNRESOLVED ISSUES

Crack control has long been considered by many state transportation agencies as a prime concern associated with the use of PSB mixtures. Although there have been a number of experimental projects related to joint placement for pozzolanic bases, there is still no universally accepted procedure for minimizing, or even possibly eliminating, shrinkage cracking in such mixtures. Addressing this issue may make possible greater acceptance and use of PSB mixtures by state transportation agencies.

Although the overwhelming majority of the PSB placed over the years has been with pozzolanic fly ash, there has been an increasing usage of self-cementing fly ash in PSB mixtures. Because the handling characteristics of self-cementing fly ash are so different from pozzolanic fly ash, more specific direction is needed on how to best handle self-cementing fly ash when used as an activator in PSB mixtures. Information needed includes how to evaluate the extent of flash setting, how to select the proper conditioning technique for different degrees of reactivity, and when and how much retarder should be used.

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INTRODUCTION

Coal fly ash can be used as a component in the production of flowable fill (also called controlled low strength material, or CLSM), which is used as self-leveling, self-compacting backfill material in lieu of compacted earth or granular fill. Flowable fill includes mixtures of Portland cement and filler material and can contain mineral admixtures, such as fly ash. Filler material usually consists of fine aggregate (in most cases, sand), but some flowable fill mixes may contain approximately equal portions of coarse and fine aggregates.(1) Fly ash has also been used as filler material.

The desired range of compressive strength in flowable fill mixtures depends largely on whether or not the hardened material may have to be excavated and removed at some future time. If removability is necessary, the ultimate strength of flowable fill should not exceed 1,035 kPa (150 lb/in^2) or jack hammers may be required for removal.(1) For flowable fill mixes used for higher bearing capacity applications, such as structural fill or temporary support of traffic loads, a greater range of compressive strength mixtures can be designed. Flowable fill is considered a controlled low strength material by ACI as long as its compressive strength is less than 8270 kPa (1,200 lb/in^2).(2) In higher strength applications, the strength of flowable fill mixes can range from 1380 to 8270 kPa (200 to 1,200 lb/in^2), depending on the design requirements of the project in question.

There are two basic types of flowable fill mixes that contain fly ash: high fly ash content mixes and low fly ash content mixes. The high fly ash content mixes typically contain nearly all fly ash, with a small percentage of Portland cement and enough water to make the mix flowable. Low fly ash content mixes typically contain a high percentage of fine aggregate or filler material (usually sand), a low percentage of fly ash and Portland cement, and enough water to make the mix flowable.(3)

There are no specific requirements for the types of fly ash that may be used in flowable fill mixtures. "Low lime" or pozzolanic (Class F) fly ash is well suited for use in high fly ash content mixes, but can also be used in low fly ash content mixes. "High lime" or self-cementing (Class C) fly ash, because it is usually self-cementing, is almost always used only in low fly ash content flowable fill mixes.(3) There is also a flowable fill product in which both Class F and Class C fly ash are used in varying mix proportions.(4)

PERFORMANCE RECORD

The use of flowable fill as a highway construction material is becoming more widespread throughout the United States. Data received from questionnaires sent by the Pennsylvania Department of Transportation (PennDOT) in 1991(5) and the Transportation Research Board (TRB) in 1992(6) indicated that approximately 30 states had some experience with the use of flowable fill, and at least 24 states have a specification for flowable fill.(6)

Most state transportation agencies have used flowable fill mainly as a trench backfill for storm drainage and utility lines on street and highway projects. Flowable fill has also been used to backfill abutments and retaining walls, to fill abandoned pipelines and utility vaults, to fill cavities and settled areas, and help to convert abandoned bridges into culverts. The most frequent use of flowable fill is reported in the states of Minnesota, Maryland, Michigan, Iowa, and Indiana.(5)

Although most states have somewhat limited experience to date with flowable fill, nearly all states that have used the material have thus far indicated satisfactory performance with little or no problems. Several states have noted that metal or plastic pipes tend to float unless anchored, and some states have reported some resistance to the use of the material by contractors or engineers.(6)

Since flowable fill is normally a comparatively low strength material, there are no strict quality requirements for fly ash used in flowable fill or CLSM mixtures. Fly ash is well suited for use in flowable fill mixtures. Its fine particle sizing (nonplastic silt) and spherical particle shape enhances mix flowability. Its relatively low dry unit weight (usually in the 890 to 1300 kg/m^3 (55 to 80 lb/ft^3) range) assists in producing a relatively lightweight fill, and its pozzolanic or cementitious properties provide for lower cement requirements than would normally be required to achieve equivalent strengths.

MATERIAL PROCESSING REQUIREMENTS

Source Control

Fly ash used in flowable fill mixes does not have to meet strict specification requirements, such as ASTM C618 for use in concrete.(7) A high-quality source of ash is not required. In addition to dry or conditioned fly ash, reclaimed ash from settling ponds may also be suitable for use in flowable fill. No special processing of fly ash or pond ash is necessary prior to its use in flowable fill mixtures.

Moisture Control

Pozzolanic fly ash can be introduced into flowable fill mixes in either a dry or moistened condition. Self-cementing fly ash should be introduced into flowable fill mixes in a dry condition to avoid presetting of this material.

ENGINEERING PROPERTIES

The engineering properties of fly ash that are the most influential in its performance in flowable fill mixtures are its spherical particle shape and pozzolanic activity with Portland cement.

Some of the engineering properties of flowable fill mixes containing fly ash that are of particular interest when fly ash is used as a principal component in flowable fill mixes include compressive strength, flowability, stability, bearing capacity, modulus of subgrade reaction, lateral pressure, time of set, bleeding and shrinkage, density, and permeability.

Compressive Strength: Strength development in flowable fill mixtures is directly related to cement content and water content, particularly when Class F fly ash is used. Most high fly ash content mixes only require from 3 to 5 percent Portland cement by dry weight of fly ash or ponded ash to develop 28-day compressive strengths in the 517 to 1034 kPa (75 to 150 lb/in^2) range. For low fly ash content mixes, Class C fly ash contributes to the strength development and can also be a complete replacement for Portland cement. Ultimate strengths may gradually increase well beyond the 28-day strength, perhaps even beyond 90 days, especially in high fly ash content mixes. As the water content is increased to produce a more flowable mix, compressive strength development will probably be somewhat lowered.(3)

Flowability: Flowability or fluidity is a measure of how well a mixture will flow when being placed. The higher the water content, the more flowable the mix. The consistency of flowable fill is probably best monitored by determining the flowability of the material. Flowability can vary from stiff to fluid depending on the job requirements. Flowability can be measured using a standard concrete slump cone,(8) a flow cone,(9) or a modified flow test using an open ended 75 mm (3 in) diameter by 150 mm (6 in) high cylinder.(16) Flowability ranges associated with the standard concrete slump cone (ASTM C143) generally vary from 150 mm (6 in) to 200 mm (8 in).(8) Admixtures (such as water reducing agents) are not normally used in flowable fill.

For high fly ash content flowable fill mixes, the slump ranges can be expected to be at least 25 to 50 mm (1 to 2 in) higher than low fly ash content mixes at comparable moisture contents.

The flow cone test (ASTM C939) is a standard procedure for determining the flow rate of grout. A desirable rate of flow for most applications of flowable fill is a time of 30 to 45 seconds through a standard flow cone.(16) The modified flow test involves filling a 75 mm (3 in) diameter by a 150 mm (6 in) cylinder mold with flowable fill, emptying the contents of the cylinder on a flat surface, and measuring the diameter of the spilled flowable fill. This test is best suited to mixtures that contain primarily fine aggregates (low fly ash content mixtures). For good flowability, the diameter of the spread material should be at least 200 mm (8 in).(16)

Stability: For low fly ash content flowable fill materials, triaxial strength tests have indicated friction angles of 20° for mixes containing fine sand and up to 30° for mixes containing concrete sand. Cohesion measured from triaxial testing has been found to vary with the compressive strength. Mixes with a 344 kPa (50 lb/in^2) compressive strength have exhibited 120 kPa (2,500 lb/ft^2) cohesion, while mixes with a 690 kPa (100 lb/in^2) compressive strength have exhibited 200 kPa (4,200 lb/ft^2) cohesion.(16)

Bearing Capacity: The allowable bearing capacity of hardened flowable fill has been shown to vary directly with compressive strength and friction angle. For example, the allowable bearing capacity for flowable fill with compressive strength of 690 kPa (100 lb/in^2) may range from 78 metric $tons/m^2$ (8 $tons/ft^2$) at a 20° friction angle to 156 metric $tons/m^2$ (16 $tons/ft^2$) at a 30° friction angle.(16) This is approximately two to four times the bearing strength of most well-compacted granular soil fill materials.

California Bearing Ratio (CBR) is also a measure of the in-place bearing strength of a subgrade material compared with that of standard crushed stone. Previous testing of flowable fill has resulted in CBR values ranging from 40 to 90 percent.(10,11) CBR testing of typical 690 kPa (100 lb/in^2) flowable fill resulted in a CBR value of 50 within 24 hours of placement. As the compressive strength of the flowable fill material increases, the CBR value can be expected to increase.

Modulus of Subgrade Reaction: The modulus of subgrade reaction (k), used for the design of rigid pavement systems, is usually in the range of 8.2 to 49.2 N/cm^3 (50 to 300 lb/in^3) for most soils and 82 N/cm^2 (500 lb/in^3) for a good granular subbase material. The k value for flowable fill is usually 820 N/cm^2 (5,000 lb/in^3) or higher, meaning it is superior to any earthen backfill it would replace.(12)

Lateral Pressure: Because of lateral fluid pressure at the time of placement, flowable fill installations at depths in excess of 1.8 m (6 ft) are normally placed in separate lifts, with each lift not exceeding 1.2 to 1.5 m (4 to 5 ft).(5) Theoretically, once flowable fill placed against a retaining wall or abutment has hardened, the lateral fluid pressure exerted during placement and initial curing should be significantly reduced. Limited load cell instrumentation of flowable fill abutment backfills has shown that flowable fills exert lateral pressure similar to that of granular materials.(13)

Time of Set: For most flowable fill mixes, especially those with high fly ash content, an increase in the cement content or a decrease in the water content, or both, should result in a reduction in hardening time. Typical high fly ash content flowable fill mixes (containing 5 percent cement) harden sufficiently to support the weight of an average person in about 3 to 4 hours, depending on the temperature and humidity. Within 24 hours, construction equipment can operate on the surface without apparent damage. Some low fly ash content flowable fill mixes, especially those containing self-cementing fly ashes, have reportedly hardened sufficiently to allow street patching within 1 to 2 hours following placement.

Bleeding and Shrinkage: High fly ash content flowable fill mixes with relatively high water contents tend to release some bleed water prior to initial set. Evaporation of the bleed water often results in a shrinkage of approximately one percent (1/8 in per ft) of flowable fill depth. The shrinkage may occur laterally as well as vertically. No additional shrinkage or long-term settlement of flowable fill occurs once the material has reached an initial set. Low fly ash content mixes, because of their high fine aggregate content and ability to more readily drain water through the flowable fill, tend to exhibit less bleeding or shrinkage than high fly ash content mixes.

Density: High fly ash content flowable fill mixes are usually lighter than compacted natural soils. Typical wet density values may range from 1460 to 1945 kg/m^3 (90 to 120 lb/ft^3), with the material being heaviest when first placed. Low fly ash content flowable fill mixes may have wet density values ranging from 1785 to 2190 kg/m^3 (110 to 135 lb/ft^3).(14) Significant decreases in density (as low as 325 kg/m^3 (20 lb/ft^3)) have been achieved in high fly ash content flowable fill mixes by the use of foaming agents in proprietary mixtures for purposes of load reduction.

Permeability: Permeability values for high fly ash content flowable fill mixtures have been found to decrease with increasing cement content and are generally in the range of 10^{-6} to 10^{-7} cm/sec.(15) Although few data are available regarding the permeability of low fly ash content flowable fill mixtures, the permeability of such mixtures is greater than that of high fly ash content mixtures, apparently in the 10^{-4} to 10^{-6} cm/sec range.(16)

DESIGN CONSIDERATIONS

Mix Design

Proportioning of flowable fill mixtures has been developed to a great extent by trial and error. Most specifications for flowable fill provide a recipe of ingredients that will produce an acceptable product, although some specifications are performance-based (usually based on a maximum compressive strength) and leave the proportioning up to the material supplier. ACI provides guidance for the mix proportioning of CLSM mixtures.(2)

High fly ash content flowable fill mixes are proportioned on the basis of the percentage of Portland cement (usually Type I cement) per dry weight of fly ash. A 5 percent Portland cement mix is fairly typical. The amount of water added to the mix is a variable that is determined by the desired degree of fluidity or flowability in the mix. When conditioned fly ash is used, the amount of water in the fly ash must be included with the amount of added water in the mix to determine the moisture content.(3)

Because low fly ash content mixes contain an additional ingredient (sand or filler), there is a broader range of mix designs, compared with high fly ash content mixes. Since fly ash is not the principal component in these mixes, the cement content is not based on a percentage of the dry weight of the fly ash in the mix, but on a percentage of the filler material and fly ash. If Class C fly ash were used, it would be used in lesser amounts than Class F fly ash because of its rapid setting characteristics.

Flowable fill mixes should be designed to develop a desired range of compressive strength. In the case of trench backfilling, a specified maximum ultimate strength (often in the 690 kPa to 1035 kPa (100 to 150 lb/in^2) range) may be the basis for design. Unconfined compressive strength testing is recommended to be performed on cylindrical test specimens (usually 75 mm (3 in) diameter by 150 mm (6 in) height) cured in sealed plastic bags at ambient temperature for 7, 14, 28, 56 and 90 days.(3)

Structural Design

Structural design procedures for flowable fill materials are no different than geotechnical design procedures used for conventional earth backfill materials. The procedures are based on using the unit weight and shear strength of the flowable fill to calculate the bearing capacity and lateral pressure of the material under given site conditions.

CONSTRUCTION PROCEDURES

Material Handling and Storage

If the fly ash to be used in a flowable fill mixture is to be mixed in a dry form (usually in low fly ash content mixes), the fly ash must be stored in a silo or pneumatic tanker until it is ready for use. Fly ash (usually Class F fly ash) that is to be used in a conditioned form in high fly ash content mixes can be stockpiled until it is ready to be used. If fly ash is stockpiled for an extended period in dry or windy weather conditions, the stockpile may need to be periodically moistened to prevent unwanted dusting.

Mixing and Placing

Flowable fill materials can be batched and mixed in pugmills, turbine mixers and central-mix concrete plants. High fly ash content flowable fill mixes have been mixed in ready-mix concrete trucks or in mobile-mix vehicles. Batching and mixing in individual mobile-mix vehicles is usually done only where small quantities of flowable fill are required at a particular location. Under such circumstances, it may be difficult to attain a uniform distribution of cement throughout the mix.

Central-mix concrete plants work especially well with low fly ash content mixes, in which a high percentage of sand is used. Essentially, the flowable fill mix is batched as a regular concrete mix without any coarse aggregate. Pugmills are well-suited to the use of ponded or conditioned ash, although a second feed bin can be added if sand (or other filler) is used.

Portable batch plants, such as those used for grouting, are often employed for on-site mixing of flowable fill materials. On-site mixing using self-cementing fly ash has been done successfully with slurry jet mixers. Dry ash is stored in large tanks on site and is pneumatically discharged through Y-shaped nozzles with metered amounts of water.(5)

Flowable fill materials are most commonly transported to the site and discharged using ready-mix concrete trucks. However, flowable fill may also be placed by means of pumps, conveyors, chutes, boxes, buckets, tremie, or in any way that concrete can be placed. Flowable fill materials require no compaction or vibration following placement.

For placement of relatively deep backfills behind abutments or retaining walls, several lifts or layers are recommended. This limits the amount of lateral pressure exerted by the flowable fill at any one time and also prevents excessive heat of hydration, especially if self-cementing fly ash is used.(5) Temperatures within the flowable fill in excess of 90° to 100°F (32° to 38°C) are normally considered excessive.(10)

When flowable fill is used to backfill pipe trenches, some lighter-weight pipes, such as corrugated metal pipes, will have to be tied down or in some way restrained to prevent them from floating as the flowable fill is being placed.

Flowable fill can be placed where water either flows or has accumulated and the flowable fill will displace the water, thus eliminating the need for pumping prior to placement. There are normally no requirements for the curing of flowable fill, although during periods of hot weather, it may be advisable to cover the exposed surfaces of flowable fills to minimize evaporation and the subsequent development of shrinkage cracking.

Quality Control

A quality assurance program is recommended to monitor the consistency, properties, and performance of flowable fill. As a minimum, such a program should consist of initial mix design testing, determination of key mix properties (such as strength development, flowability, setting time and density), and field testing of these properties, with flowability considered the most important quality control parameter to be monitored in the field prior to placement of the material.

Special Conditions

Flowable fill materials do develop some heat of hydration in place, especially those that contain self-cementing fly ash. Consequently, flowable fill can be placed at, or even possibly somewhat below, freezing temperatures. However, heated water should be used and the excess bleed water at the flowable fill surface should have the opportunity to dissipate so that it does not freeze. Also, a protective layer should be placed above the top surface of the flowable fill to minimize or prevent freeze-thaw damage. Ice or frozen surface material should be removed before placing additional layers of either flowable fill or pavement material.(6)

UNRESOLVED ISSUES

Although there are a wide variety of mix designs for flowable fill, some standardization of mix design methods is needed. The use of concrete admixtures (such as air-entraining agents) in flowable fill mixtures needs further investigation. More data are needed on long-term strength development of various flowable fill mix designs. More experience is needed in the setting time and rate of strength development of low fly ash content mixes containing self-cementing fly ash. Additional information is also needed on the engineering properties and performance of other by-products (foundry sand, quarry fines, etc.) as filler materials in low fly ash content mixes.

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ORIGIN

The burning of pulverized coal in electric power plants produces sulfur dioxide (SO_2) gas emissions. The 1990 Clean Air Act and its subsequent amendments mandated the reduction of power plant SO_2 emissions. The Best Demonstrated Available Technology (BDAT) for reducing SO_2 emissions is wet scrubber flue gas desulfurization (FGD) systems. These systems are designed to introduce an alkaline sorbent consisting of lime or limestone (primarily limestone) in a spray form into the exhaust gas system of a coal-fired boiler. The alkali reacts with the SO_2 gas and is collected in a liquid form as calcium sulfite or calcium sulfate slurry. The calcium sulfite or sulfate is allowed to settle out as most of the water is recycled.

FGD scrubber sludge is the wet solid residue generated from the treatment of these emissions. The wet scrubber discharge is an off-white slurry with a solids content in the range of 5 to 10 percent. Because FGD systems are usually accompanied by or combined with a fly ash removal system, fly ash is often incorporated into the FGD sludge.

The relative proportion of the sulfite and sulfate constituents is very important in determining the physical properties of FGD sludges. Depending on the type of process and sorbent material used, the calcium sulfite ($CaSO_3$) can contribute anywhere from 20 to 90 percent of the available sulfur, the remaining being calcium sulfate ($CaSO_4$). FGD sludges with high concentrations of sulfite pose a significant dewatering problem, because the sulfite sludges settle and filter poorly. They are thixotropic and generally not suitable for land disposal or management without additional treatment (a thixotropic material appears as a solid, but will liquify when vibrated or agitated). Treatment can include forced oxidation, dewatering, and/or fixation or stabilization.

Forced oxidation, which is a separate step after the actual desulfurization process, involves blowing air into the tank that holds calcium sulfite sludge, and results in the oxidation of the calcium sulfite ($CaSO_3$) to calcium sulfate ($CaSO_4$). The calcium sulfate formed by this reaction grows to a larger crystal size than calcium sulfite. As a result, the calcium sulfate can be filtered or dewatered to a much drier and more stable material than the calcium sulfite sludge.(1) Dewatering of FGD scrubber sludge is ordinarily accomplished by centrifuges or belt filter presses.

Fixation and stabilization are terms that are often used interchangeably when referring to FGD sludge treatment. In general, stabilization of FGD scrubber material refers to the addition of a sufficient amount of dry material, such as fly ash, to the dewatered FGD filter cake so that the stabilized material can be handled and transported by construction equipment without water seepage and can also support normal compaction machinery when placed into a landfill. Stabilization is primarily the result of physical reactions between the FGD sludge cake and the added drying agent.

Fixation ordinarily refers to the addition of sufficient chemical reagent(s) to convert the stabilized FGD scrubber material into a solidified mass and produce a material of sufficient strength to satisfy applicable structural specifications. This can involve the addition of Portland cement, lime, and/or self-cementing fly ash to induce both physical and chemical reactions between the stabilized sludge filter cake and the added reagents. The majority of the fixation processes currently in operation involve the addition of quicklime and pozzolanic fly ash, resulting in a pozzolanic reaction that provides added strength to dewatered FGD scrubber material.

Figure 6-1 presents an illustration of typical FGD processing, reuse, or disposal options.

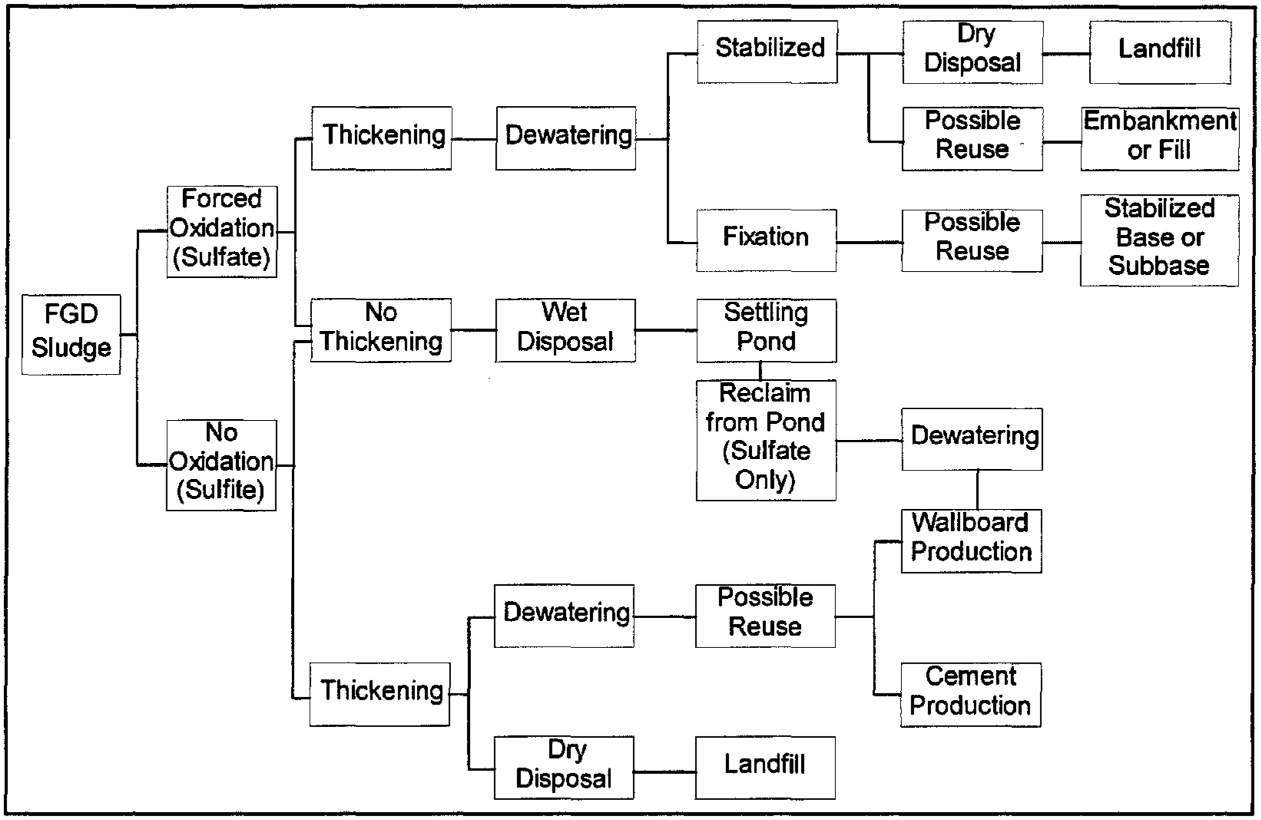

Figure 6-1. FGD sludge processing system.(2)

As of December 1994, there were at least 157 coal-fired boiler units at 92 power plants that had operating wet scrubbing systems. These plants are located in at least 32 states.(3) Additional scrubbers are planned or under construction in order to achieve compliance with the Clean Air Act requirements. As of 1996, the operating scrubber systems at coal-fired power plants generated approximately 21.4 million metric tons (23.8 million tons) of FGD sludge annually.(4)

CURRENT MANAGEMENT OPTIONS

Recycling

Fixated or stabilized calcium sulfite FGD scrubber material has been used as an embankment and road base material. Oxidized (calcium sulfate) FGD scrubber material, once it has been dewatered, has been sold to wallboard manufacturers as by-product gypsum.(2) This material has also been used as feed material, in place of gypsum, for the production of Portland cement. Oxidized FGD scrubber material (calcium sulfate) does not require fixation or stabilization for use as wallboard gypsum, but merely drying to a required solids content. Wallboard production represents the largest single market for FGD scrubber material.(2)

Although there is significant interest in using calcium sulfate FGD scrubber material in wallboard construction and in Portland cement production (as a gypsum source), relatively small amounts of calcium sulfate FGD scrubber material are presently being recycled. In 1996, approximately 0.8 million metric tons (0.9 million tons) of calcium sulfate FGD scrubber material were used to produce wallboard and approximately 0.06 million metric tons (0.07 million tons) of this material were used as feed material for cement production.(3) Also in 1996, approximately 0.04 million metric tons (0.05 million tons) of primarily fixated calcium sulfite FGD scrubber material were used for structural fill. Also, approximately 0.11 million metric tons (0.12 million tons) were used for road base construction.(3)

Disposal

Almost all FGD scrubber sludge generated at the present time is disposed of in holding ponds or in landfills. Stabilization or fixation and placement in landfills is the most common method of disposal.

MARKET SOURCES

Fixated FGD scrubber material is generated, dewatered, and stabilized at utility coal-burning power plants that burn either medium- or high-sulfur coals that require scrubbing of the flue gas emissions to reduce sulfur dioxide levels. For FGD scrubber sludge to be a useable construction material that is suitable for recycling, it must first be dewatered, then stabilized or fixated. The scrubber sludge must also be dewatered and stabilized to enable its placement and compaction in a landfill.

The majority of the utility coal-fired power plants that are equipped with FGD scrubber systems dewater and stabilize the FGD scrubber sludge so that it can be placed in a landfill. The dewatering and stabilization (or fixation) steps are usually handled by the utility company, while the loading, transport, placement, and compaction of the stabilized or fixated FGD scrubber material are usually handled by an ash management contractor. Stabilized or fixated FGD scrubber material can be obtained from either the utility company or the ash management contractor at a particular power plant where FGD scrubbers are in operation.

Fixated or stabilized calcium sulfite FGD sludge filter cake can have a solids content from 55 to 80 percent, depending on the amount of fly ash in the blend. The resultant fixated FGD sludge product is a damp, gray, silty, compactable material capable of supporting normal construction equipment and developing compressive strength.(5)

HIGHWAY USES AND PROCESSING REQUIREMENTS

Stabilized Base

Stabilized or fixated FGD scrubber material has been used successfully for road base construction, as previously noted, at a number of different sites in Florida, Pennsylvania, Ohio, and Texas. (See references 6,7,8 and 9). Stabilization or fixation of FGD scrubber material (especially calcium sulfite sludge) can be accomplished by the addition of quicklime and pozzolanic fly ash, Portland cement, or self-cementing fly ash. Other activators may be used in place of quicklime. The FGD scrubber sludge is dewatered before the addition of stabilization or fixation reagents. Additional fixation reagents may need to be added for stabilized base construction in order to meet compressive strength or durability requirements.

Embankments

Small amounts of fixated FGD scrubber material have been used for embankment construction in western Pennsylvania.(10) The material was reclaimed from a landfill and used in conjunction with a fly ash embankment project. No additional reagents were needed for embankment construction.

MATERIAL PROPERTIES

Physical Properties

Dewatered FGD scrubber material is most frequently generated as calcium sulfite, although some power plant scrubbing systems are of forced oxidation design, resulting in a calcium sulfate (or by-product gypsum) material. Calcium sulfite FGD scrubber material is fixated and used for road base, while the calcium sulfate FGD scrubber material is frequently used for wallboard or as a cement additive. Table 6-1 shows the difference in typical physical properties (particle size and specific gravity) between calcium sulfite and calcium sulfate FGD scrubber material.(11) The oxidized material is coarser than the unoxidized material.

Table 6-1. Typical physical properties of FGD scrubber material.

Property	(Unoxidized) Calcium Sulfite	(Oxidized) Calcium Sulfate
Particle Sizing (%)		
Sand Size	1.3	16.5
Silt Size	90.2	81.3
Clay Size	8.5	2.2
Specific Gravity	2.57	2.36

The degree to which FGD scrubber material is treated influences its physical properties. Table 6-2 shows the physical characteristics of typical calcium sulfite FGD scrubber material in its dewatered, physically stabilized, and fixated conditions. Basic physical properties include solids content, moisture content, specific gravity, and wet and dry density.(7)

Table 6-2. Physical characteristics of typical calcium sulfite FGD scrubber material.

Physical Property	Dewatered	Stabilized	Fixated
Solids Content (%)	40 - 65	55 - 80	60 - 80
Specific Gravity	2.25 - 2.60	2.25 - 2.60	2.25 - 2.60
Wet Density (kg/m^3)	1,460 - 1,780	1,460 - 1,780	1,540 - 1,860
(lb/ft^3)	90 - 110	90 - 110	95 - 115
Dry Density (kg/m^3)	970 - 1,280	1,210 - 1,540	970 - 1,650
(lb/ft^3)	60- 80	75 - 95	80 - 102

When dewatered, the calcium sulfite FGD sludges become a soft filter cake with a solids content typically in the 40 to 65 percent range. Calcium sulfate FGD sludges can be dewatered much more easily and may achieve solids contents up to as high as 70 to 75 percent after dewatering.(12)

Dewatered and unstabilized calcium sulfite FGD scrubber sludge consists of fine silt-clay sized particles with approximately 50 percent finer than 0.045 mm (No. 325 sieve). It has a dry density in the range of 960 to 1,280 kg/m^3 (60 to 80 lb/ft^3), with a specific gravity of solids in the 2.4 range.(13)

The solids contents of fixated FGD scrubber material ordinarily range from 60 to 80 percent. The specific gravity of fixated FGD sulfite scrubber material can range from 2.25 to 2.60, with an average of 2.38. Between 88 and 98 percent of the particles are in the silt size range. Depending on the amount of fly ash in the blend, maximum dry density values of fixated FGD scrubber material can range from 1,280 to 1,600 kg/m^3 (80 to 102 lb/ft^3) at optimum moisture contents ranging from 20 to 30 percent when tested using the standard Proctor (ASTM D698)(14) test method.(15)

Chemical Properties

The chemical composition of FGD scrubber material varies according to the scrubbing process, type of coal, sulfur content, and presence or absence of fly ash. Lime is the most commonly used reagent in the scrubbing process. Table 6-3 lists the major components of FGD scrubber material prior to dewatering or fixation.(11) This table indicates the normally expected percentage ranges of calcium sulfite, sulfate, or carbonate that result from the scrubbing of flue gases using various processes. Except for those subjected to forced oxidation, sludges from the scrubbing of bituminous coals are generally sulfite-rich, whereas forced oxidation sludges and sludges generated from scrubbing of subbituminous and lignite coals are sulfate-rich. Fly ash is a principal constituent of FGD scrubber material only if the scrubber serves as a particulate control device in addition to SO_2 removal or if separately collected fly ash is mixed with the sludge.(11)

Table 6-3. Major components of FGD scrubber material from different coal types and scrubbing processes (percent by weight).

Type of Coal	Sulfur Content	Type of Process	$CaSO_3$	$CaSO_4$	$CaCO_3$	Fly Ash
Bituminous	2.9 - 4.0	Lime	50 - 94	2 - 6	0 - 3	4 - 41
Bituminous	2.9	Limestone	19 - 23	15 - 32	4 - 42	20 - 43
Bituminous	1.0 - 4.0	Dual Alkali (Calcium-Sodium)	65 - 90	5 - 25	2 - 10	0
Bituminous	2.0 - 3.0	Lime (Forced Oxidation)	0 - 3	52 - 65	2 - 5	30 - 40
Lignite	0.6	Fly Ash (Class C)	0 - 5	5 - 20	0	40 - 70
Subbituminous	0.5 - 1.0	Limestone	0 - 20	10 - 30	20 - 40	20 - 60

As shown in Table 6-3, the use of limestone as a sorbent with bituminous coals results in significantly lower percentages of calcium sulfite ($CaSO_3$) and higher percentages of calcium sulfate ($CaSO_4$) and calcium carbonate ($CaCO_3$) than the use of lime as a sorbent with bituminous coals.

Mechanical Properties

Table 6-4 shows the expected range of mechanical properties (permeability, shear strength, and unconfined compressive strength) for dewatered, stabilized, and fixated calcium sulfite FGD scrubber material.

Table 6-4. Mechanical properties of typical calcium sulfite FGD scrubber material.

Mechanical Property	Dewatered	Stabilized	Fixated
Shear Strength - Internal Friction Angle	20°	35° - 45°	35° - 45°
Permeability (cm/sec)	10^{-4} to 10^{--5}	10^{-6} to 10^{-7}	10^{-6} to 10^{-8}
28-Day Unconfined Compressive Strength (kPa)	–	170 - 340	340 - 1,380
(lb/in^2)	–	25 - 50	50 - 200

Dewatered unstabilized calcium sulfite FGD scrubber sludges have a pastelike consistency with low shear strength and little bearing capacity. They are thixotropic, meaning that, when agitated, they revert to a liquid or slurry form. They have no unconfined compressive strength, an angle of internal friction around 20°, and a permeability in the range of 10^{-4} to 10^{-5} cm/sec.(9)

Stabilized or fixated calcium sulfite FGD scrubber material has unconfined compressive strength values in the range of 170 kPa (25 lb/in^2) to 1380 kPa (200 lb/in^2), an angle of internal friction of 35° to 45°, and coefficient of permeability values in the range of 10^{-6} to 10^{-7} cm/sec.(5)

If stabilized or fixated FGD scrubber sludge is to be used for road base construction, then the unconfined compressive strength is more likely to be in the range of 1720 kPa (250 lb/in^2) to as high as 6900 kPa (1,000 lb/in^2), depending on specification requirements and reagent addition rates. The flexural strength of stabilized FGD sludge road base materials is normally in the 690 to 1,720 kPa (100 to 250 lb/in^2) range.(16) To achieve these strength ranges, additional fixation reagents (Portland cement, lime, fly ash, etc.) will usually be required.

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INTRODUCTION

Fixated or stabilized flue gas desulfurization (FGD) scrubber material can be used as a stabilized base and/or subbase material. The fixated FGD scrubber material is produced in a compactable condition and can be used in essentially the same manner as other lime-fly ash or cement-stabilized base materials. The fixated FGD scrubber material may be used in its "as produced" condition, provided it is capable of developing the required compressive strength and satisfying durability requirements. If this is not the case, then additional fixation reagent (Portland cement, lime, fly ash, etc.) must be blended with the fixated FGD scrubber material to ensure that it does meet strength and durability criteria. Besides additional fixation reagent, an aggregate material (usually coal bottom ash) can also be blended with the fixated FGD scrubber material. Properly designed fixated FGD scrubber material has comparable strength development and durability characteristics to that of conventional stabilized base materials.

PERFORMANCE RECORD

The earliest known application in which FGD scrubber material was used in stabilized base compositions occurred during the construction of the TRANSPO'72 International Transportation Exposition held in 1972 at Dulles Airport near Washington, D.C. A portion of the new 40 hectare (100 acre) parking area was used by the FHWA to demonstrate the potential for use of base course mixtures containing a number of calcium sulfate type wastes, including FGD scrubber material.

The demonstration parking area at the exposition was paved with a 127 mm (5 in) thick compacted stabilized base mixture containing 3 percent lime, 59 percent fly ash, 17 percent bottom ash, 13 percent crushed limestone, and 8 percent dewatered FGD scrubber material.(1) The overall results from the demonstration indicated that FGD scrubber material was potentially useful for highway base course construction. However a combination of poor weather and saturated subgrade conditions at the time of construction contributed to a softening and loss of density and eventually resulted in the removal and replacement of the experimental base material.(2)

Besides its use in TRANSPO'72, fixated FGD scrubber material has been used in stabilized base applications in at least four other states. These applications are listed in Table 6-5.

Table 6-5. Summary of fixated FGD scrubber material use in stabilized base and subbase applications in the United States.

State	Estimated Number of Projects	Time Period	Types of Projects	Remarks
Florida (3)	At least 12	1977-89	Parking lots Private roads County roads	Satisfactory performance. No freeze-thaw concerns.
Pennsylvania (4)	At least 1	1977	State secondary road	Successful performance. Severe freeze-thaw cycles.
Texas (5)	At least 2	1993	Private road Demonstration	Successful performance to date. Wetting and drying exposure.
Ohio (6)	At least 1	1995	Power plant road Demonstration	Successful performance to data. Severe freeze-thaw cycles.

In Florida, crushed lime rock is widely available and commonly used as a roadbase construction material. A typical county road section consists of from 152 mm (6 in) to 305 mm (12 in) of lime rock base placed on a prepared subgrade and overlaid with 50 mm (2 in) to 76 mm (3 in) of asphalt wearing surface. Laboratory test data from the University of Florida indicated that base course compositions of lime-fly ash-dewatered FGD scrubber sludge (referred to as Poz-o-Tec) had better bearing strength characteristics than lime rock base.(3)

Between 1977 and 1989, 12 different projects were constructed in central Florida in which FGD material was used as the base course. These projects consisted of one truck haul road, three parking lots, one landfill access road, one private access road, one heavy steel storage yard, one utility plant access road, and four city or county roads. The base course thicknesses for these projects varied from 152 mm (6 in) to 305 mm (12 in). At least 90,000 metric tons (100,000 tons) of fixated FGD base have been placed in Florida. Performance has been reported as highly satisfactory.(3)

In 1977, a 244 m (800 ft) long section of pozzolanic road base material composed of lime, fly ash, bottom ash, and dewatered FGD scrubber material was placed as a demonstration on a state secondary road in southwestern Pennsylvania. The entire base was placed in one day in a single lift at a compacted thickness of 25 mm (10 in). The base was covered by a 50 mm (2 in) bituminous concrete binder course and a 25 mm (1 in) bituminous concrete wearing surface.

Test data and visual observations over a 7-year period following installation have demonstrated fully successful performance. Despite severe freeze-thaw cycles, the road exhibited no potholes or broken areas and the base remained intact as verified by periodic coring. The average unconfined compressive strength of road base cores was 4,960 kPa (720 lb/in^2) after 1 year, 5,800 kPa (840 lb/in^2) after 3 years, and 6,990 kPa (1014 lb/in^2) after 7 years.(4)

Two demonstration test sections, each 5.6 m (18 ft) wide, 92 m (300 ft) long, and 305 mm (12 in) thick, were constructed during December 1993 at the Riverside Campus of Texas A&M University. The first test section consisted of fixated FGD sludge (sometimes referred to in Texas as scrubber base), which consisted of a blend of self-cementing fly ash with dewatered FGD sludge, to which was added coal bottom ash and additional self-cementing fly ash. The second test section consisted of the fixated FGD material blended with type II Portland cement.

The two experimental sections were constructed by spreading the component materials with a motor grader and mixing in place with a pulvi-mixer. A control section, also 93 m (300 ft) long, was also placed between the two experimental sections. The control section consisted of 305 mm (12 in) of crushed iron ore gravel. After 2 years of monitoring, both of the FGD scrubber sludge base sections demonstrated significantly higher strength and stiffness than the control section.(5)

In June 1995, a 77 m (250 ft) long test section of cement-bottom ash-fixated FGD scrubber sludge base material was placed as part of a 232 m (750 ft) long demonstration haul road at the Gavin power plant in Cheshire, Ohio. The fixated FGD scrubber sludge material consisted of 3 percent quick lime and 70 percent pozzolanic fly ash added to one part by dry weight of dewatered FGD scrubber sludge. The base course mix design involved a blend of 40 percent bottom ash and 60 percent fixated FGD scrubber sludge, to which was added 7 percent Portland cement. The base course mix was produced in a pugmill mixing plant.

The cement-bottom ash-fixated FGD scrubber sludge base was placed at a compacted thickness of 203 mm (8 in) and overlaid with 76 mm (3 in) of asphalt paving. The haul road is used extensively by heavy trucks on a daily basis and has survived one winter and more than one full year of use with no noticeable signs of distress.(6)

MATERIAL PROCESSING REQUIREMENTS

Dewatering

The calcium sulfite scrubber material from FGD systems is generally of toothpastelike consistency (from 25 to 50 percent solids) after the sludge has been dewatered. Dewatering is usually accomplished by belt filter presses or centrifuges. Centrifuges are normally able to dewater the sludge to a higher solids content than filter presses.

Stabilization/Fixation

Dewatered FGD material must be stabilized or fixated by the addition of dry reagents (quicklime and Class F fly ash, Class C fly ash, or Portland cement) before being converted to a compactable consistency (at least 65 to 70 percent solids) for use in stabilized base compositions. The fixated FGD scrubber material can then be placed and compacted as a base material or, if necessary to meet strength and durability requirements, blended with additional reagent and, in some cases, aggregate or bottom ash prior to being used as a stabilized base or subbase.

ENGINEERING PROPERTIES

Some of the properties of FGD scrubber sludge that are of particular interest when FGD scrubber sludge is incorporated into stabilized bases and subbases include particle size distribution, moisture content, wet and dry density, permeability, moisture-density characteristics, compressive strength, and durability.

<u>Particle Size Distribution</u>: Unoxidized calcium sulfite is composed of approximately 90 percent silt, 8.5 percent clay, and 1.5 percent sand sizes. Oxidized calcium sulfate is composed of approximately 81 percent silt, 16.5 percent sand, and 2.5 percent silt sizes.(7)

<u>Moisture Content</u>: Dewatered calcium sulfite is the FGD scrubber material that is usually stabilized or fixated and used for road base. Prior to dewatering, the calcium sulfite slurry has a moisture content of approximately 60 percent. After dewatering, the moisture content is reduced to roughly 25 percent. Following stabilization or fixation, the FGD scrubber material has a moisture content in the 15 to 20 percent range.(7)

<u>Wet and Dry Density</u>: In slurry form, FGD scrubber sludge has a wet density between 1,500 kg/m^3 (95 lb/ft^3) and 1,600 kg/m^3 (100 lb/ft^3) and a dry density between 950 kg/m^3 (60 lb/ft^3) and 1,050 kg/m^3 (65 lb/ft^3). In dewatered form, the FGD filter cake has a wet density between 1,600 kg/m^3 (100 lb/ft^3) and 1,800 kg/m^3 (110 lb/ft^3) and a dry density between 1,200 kg/m^3 (75 lb/ft^3) and 1,400 kg/m^3 (85 lb/ft^3). In stabilized or fixated form, the FGD scrubber material has a wet density between 1,700 kg/m^3 (105 lb/ft^3) and 1,900 kg/m^3 (115 lb/ft^3) and a dry density between 1,450 kg/m^3 (90 lb/ft^3) and 1,600 kg/m^3 (100 lb/ft^3).(7)

<u>Permeability</u>: As FGD scrubber material is successively reduced in moisture content through dewatering or stabilization, the permeability of the material also decreases. Prior to dewatering,

calcium sulfite slurry has a permeability of 8×10^{-5} cm/sec. After dewatering, the filter cake has a permeability of 1×10^{-5} cm/sec. Shortly after stabilization, the permeability is about 1×10^{-6} cm/sec. After fixation, the permeability may be as low as 5×10^{-8} cm/sec.(7)

Moisture-Density Characteristics: Depending on the properties of the dewatered FGD scrubber material and the mix design proportions and reagents used for stabilization or fixation, the maximum dry density values of fixated FGD scrubber material may range from 1,300 to 1,650 kg/m^3 (80 to 102 lb/ft^3), with optimum moisture normally between 11 and 19 percent when tested in accordance with the standard Proctor (ASTM D698)(8) method.(9)

Compressive Strength: The compressive strength of most fixated FGD material base course mixtures continues to increase over time. Strength gain is more gradual with pozzolanic stabilized mixtures than mixtures stabilized with Portland cement or Class C fly ash. After 7 days, compressive strengths can range from 1,400 kPa (200 lb/in^2) to 2,800 kPa (400 lb/in^2) for pozzolanic stabilized mixtures and from 4,100 kPa (600 lb/in^2) to 6,200 kPa (900 lb/in^2) for mixtures stabilized with Portland cement or Class C fly ash. These strengths continue to increase over time and can exceed 13.8 MPa (2,000 lb/in^2) after 1 or more years.

Durability: Durability testing of fixated FGD scrubber material may involve either freeze-thaw or wet-dry testing, or both. Freeze-thaw testing should be performed in accordance with ASTM D560(10) procedures. Wet-dry testing should be performed in accordance with ASTM D559(11) procedures. There has been limited durability testing of fixated FGD scrubber materials. Generally, stabilized base or subbase mixtures containing fixated FGD scrubber material that achieve between 2,800 kPa (400 lb/in^2) and 4,500 kPa (650 lb/in^2) compressive strength within 7 days will pass durability tests.

DESIGN CONSIDERATIONS

Mix Design

Mix design for FGD scrubber sludge mixes involves blending fixated FGD sludge with one or more stabilization reagents (lime, fly ash, or Portland cement), and possibly also including coal bottom ash or conventional aggregate. As with other stabilized base mixes, mix design proportions must be developed to meet the requirements of ASTM C593.(12)

Unless otherwise specified, a minimum unconfined compressive strength of 2,800 kPa (400 lb/in^2) is recommended after ambient curing for at least 14 days, but no longer than 28 days. If Portland cement is used as the stabilization reagent, some states require 4,500 kPa (650 lb/in^2) unconfined compressive strength after curing for 7 days.

Mixes containing fixated FGD scrubber material should be tested for moisture-density relationships and molded as close as possible to optimum moisture content and maximum dry density. If bottom ash is used as an aggregate, the ratio of FGD scrubber sludge to bottom ash is often in the 1.5:1 to 1:1 range. The addition of bottom ash usually enhances the strength development of stabilized base mixes.

When using Portland cement as a stabilization reagent, Type II (moderately sulfate resistant) cement should be used. When a pozzolanic fly ash and quicklime are used to stabilize the FGD scrubber material, adequate strength can usually be achieved by the addition of up to 7 to 8 percent cement by weight of dry solids, or by adding more quicklime. If a self-cementing fly ash is used as the FGD material fixation reagent, then adding a lower percentage of cement (possibly 3 to 4 percent) or the addition of more fly ash may be needed to achieve the required strength.

Structural Design

The thickness design of stabilized base or subbase mixtures containing fixated FGD scrubber material can be undertaken using the structural equivalency design method described in the AASHTO Design Guide.(13) This method uses an empirical structural number (SN) that relates pavement layer thickness to performance.

Table 6-6 lists recommended structural coefficient values for stabilized base or subbase mixtures. These coefficient values are based on the use of $a_1 = 0.44$ (used for a bituminous wearing surface) and a value of $a_3 = 0.15$ (used for a crushed stone base), and are derived from studies of pozzolanic and crushed stone base materials performed at the University of Illinois.(14)

Table 6-6. Recommended structural coefficient values for stabilized base mixtures.

Quality	Compressive Strength, kPa (lb/in^2) (7 days @ 38°C (100°F)	Recommended Structural Layer Coefficient
High	Greater than 6,900 (1,000)	$a_2 = 0.34$
Average	4,500 to 6,900 (650 to 1,000)	$a_2 = 0.28$
Low	2,800 to 4,500 (400 to 650)	$a_2 = 0.20$

Structural layer coefficient values of 0.30 to 0.35 have been recommended for Portland cement-stabilized bases.(15) Compressive strength development in laboratory-cured cement-stabilized test specimens is ordinarily determined under ambient temperature conditions, rather than 38 °C (100 °F) conditions.

The main factors influencing the selection of the structural layer coefficient for thickness design using the AASHTO method are the compressive strength and modulus of elasticity of the stabilized base material. The value of compressive strength recommended for determination of the structural layer coefficient is the field design compressive strength. The field design compressive strength is simulated by the compressive strength developed in the laboratory after 56 days of moist curing at 23 °C (73 °F).(15) However, other curing conditions may be required by various specifying agencies.

CONSTRUCTION PROCEDURES

Construction procedures for stabilized base and subbase mixtures in which fixated FGD scrubber material is used are essentially the same as those used for more conventional pozzolanic stabilized bases and subbases.

Material Handling and Storage

Fixated FGD scrubber material is usually stockpiled on a concrete pad for a period of as much as 24 hours. The material can then be blended with additional reagent (such as lime or Portland cement), blended with bottom ash, boiler slag or other aggregate, or simply transported and placed as is on the job site.

Mixing, Placing, and Compacting

The blending or mixing of dewatered FGD scrubber material with appropriate reagents in stabilized base mixtures can best be done in a mixing plant. Plant mixing is recommended because it provides greater control over the quantities of materials batched and also results in the production of a more uniform mixture. Because of the toothpaste-like consistency of dewatered FGD scrubber material, mixing in place with reagents is not recommended.

To develop the design strength of a stabilized base mixture, the material must be well-compacted and must be as close as possible to its optimum moisture content when placed. Fixated FGD scrubber materials should be delivered to the job site as soon as possible after mixing and should be compacted as soon as possible after placement. This is particularly the case with mixtures in which Class C fly ash is used as an activator.

Fixated FGD scrubber base materials should not be placed in layers that are less than 100 mm (4 in) or greater than 20 to 22 cm (8 to 9 in) in compacted thickness. These materials should be spread in loose layers that are approximately 50 mm (2 in) greater in thickness prior to compaction than the desired compacted thickness. The top surface of an underlying layer should be scarified prior to placing the next layer. Smooth drum, steelwheeled vibratory rollers are most frequently used for compaction, although satisfactory compaction results have also been obtained using smooth drum, steelwheeled static rollers. The smooth drum roller also seals the surface of the road base to minimize adverse impacts from rainfall.(3)

Curing

After placement and compaction, the fixated FGD scrubber base material must be properly cured to protect against drying and assist in the development of in-place strength. An asphalt emulsion seal coat should be applied to the top surface of the stabilized base or subbase material. For most types of stabilized base materials, the seal coat is applied within 24 hours after placement.

Placement of asphalt paving over the stabilized base is recommended within 7 days after the base has been installed. Unless an asphalt binder and/or surface course has been placed over the stabilized base material, vehicles should not be permitted to drive over the material until it has achieved an in-place compressive strength of at least 2,410 kPa (350 lb/in^2).(15)

Special Considerations

Cold Weather Construction

Stabilized base materials containing fixated FGD scrubber material that are subjected to freezing and thawing conditions must be able to develop a certain level of cementing action and in-place strength prior to the first freeze-thaw cycle in order to withstand the disruptive forces of such cycles. For northern states, many state transportation agencies have established construction cut-off dates for stabilized base materials. These cutoff dates ordinarily range from September 15 to October 15, depending on the state, or the location within a particular state, as well as the ability of the stabilized base mixture to develop a minimum desired compressive strength within a specified time period.(15)

Use of Self-Cementing Fly Ash

When self-cementing fly ashes are used as an activator in stabilized base mixtures, including those containing fixated FGD scrubber material, compaction should be accomplished as soon as possible after mixing. Otherwise, delays between placement and compaction of such mixtures may be accompanied by a significant decrease in the strength of the compacted stabilized base material.(16)

Crack Control Techniques

Fixated FGD scrubber base materials, especially those in which Portland cement is used as the reagent, may be subject to crack development. The cracks are almost always shrinkage related and are not the result of any structural weakness or defects in the stabilized base material. Unfortunately, shrinkage cracks eventually reflect through the overlying asphalt pavement and must be sealed at the pavement surface to prevent water intrusion and subsequent damage due to freezing and thawing. Cracking is also likely to occur when FGD scrubber material is blended or fixated with quicklime and pozzolanic fly ash, or with self-cementing fly ash.

Recommended methods for minimizing reflective cracking associated with shrinkage cracks is to saw cut transverse joints in the asphalt surface that extend into the stabilized base material to a depth of 75 mm (3 in) to 100 mm (4 in). Joint spacings of approximately 9 m (30 ft) have been suggested.(15) For parking lots, the joints should be cut in two directions, perpendicular to each other at approximately the same spacing. The joints should all be sealed using a hot poured asphaltic joint sealant.

UNRESOLVED ISSUES

Although field installations of stabilized base course materials containing fixated FGD scrubber material have almost always been successful, scrubber sludge is perceived as an unusual, difficult to handle material. There is a general lack of knowledge and understanding of how FGD scrubber material can be converted from a sloppy, unstable mess before dewatering into a competent engineering material after being dewatered and fixated (by being blended with other aggregates and reagents) to form a quality road base material.

More laboratory mix design work is needed to develop suitable base course mixtures in which dewatered FGD material is blended with Portland cement or self-cementing fly ash and a variety of unconventional aggregate sources, such as coal bottom ash, reclaimed paving materials, nonferrous slags, or mineral by-products. More fixated FGD field installations also need to be placed, monitored for performance over several years, and documented in order to demonstrate to the highway engineering community that properly designed fixated FGD material can produce excellent base courses.

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ORIGIN

Foundry sand consists primarily of clean, uniformly sized, high-quality silica sand or lake sand that is bonded to form molds for ferrous (iron and steel) and nonferrous (copper, aluminum, brass) metal castings. Although these sands are clean prior to use, after casting they may contain a number of components (such as tramp metals and residual binder materials) that are introduced during molding or picked up from the metal casting. Ferrous (iron and steel) industries account for approximately 95 percent of foundry sand used for castings. The automotive industry and its parts suppliers are the major generators of foundry sand.

The most common casting process used in the foundry industry is the sand cast system. Virtually all sand cast molds for ferrous castings are of the green sand type. Green sand consists of high-quality silica sand, about 10 percent bentonite clay (as the binder), 2 to 5 percent water and about 5 percent sea coal (a carbonaceous mold additive to improve casting finish). The type of metal being cast determines which additives and what gradation of sand is used. The green sand used in the process constitutes upwards of 90 percent of the molding materials used.(1)

In addition to green sand molds, chemically bonded sand cast systems are also used. These systems involve the use of one or more organic binders (usually proprietary) in conjunction with catalysts and different hardening/setting procedures. Foundry sand makes up about 97 percent of this mixture. Chemically bonded systems are most often used for "cores" (used to produce cavities that are not practical to produce by normal molding operations) and for molds for nonferrous castings.

The annual generation of foundry waste (including dust and spent foundry sand) in the United States is believed to range from 9 to 13.6 million metric tons (10 to 15 million tons).(2) Typically, about 1 ton of foundry sand is required for each ton of iron or steel casting produced.

Additional information on the production and use of spent foundry sand in construction materials applications can be obtained from:

American Foundrymen's Society, Inc.
505 State Street
Des Plaines, Illinois 60016-8399

CURRENT MANAGEMENT OPTIONS

Recycling

In typical foundry processes, sand from collapsed molds or cores can be reclaimed and reused. A simplified diagram depicting the flow of sand in a typical green sand molding system is presented in Figure 7-1. Some new sand and binder is typically added to maintain the quality of the casting and to make up for sand lost during normal operations.(3)

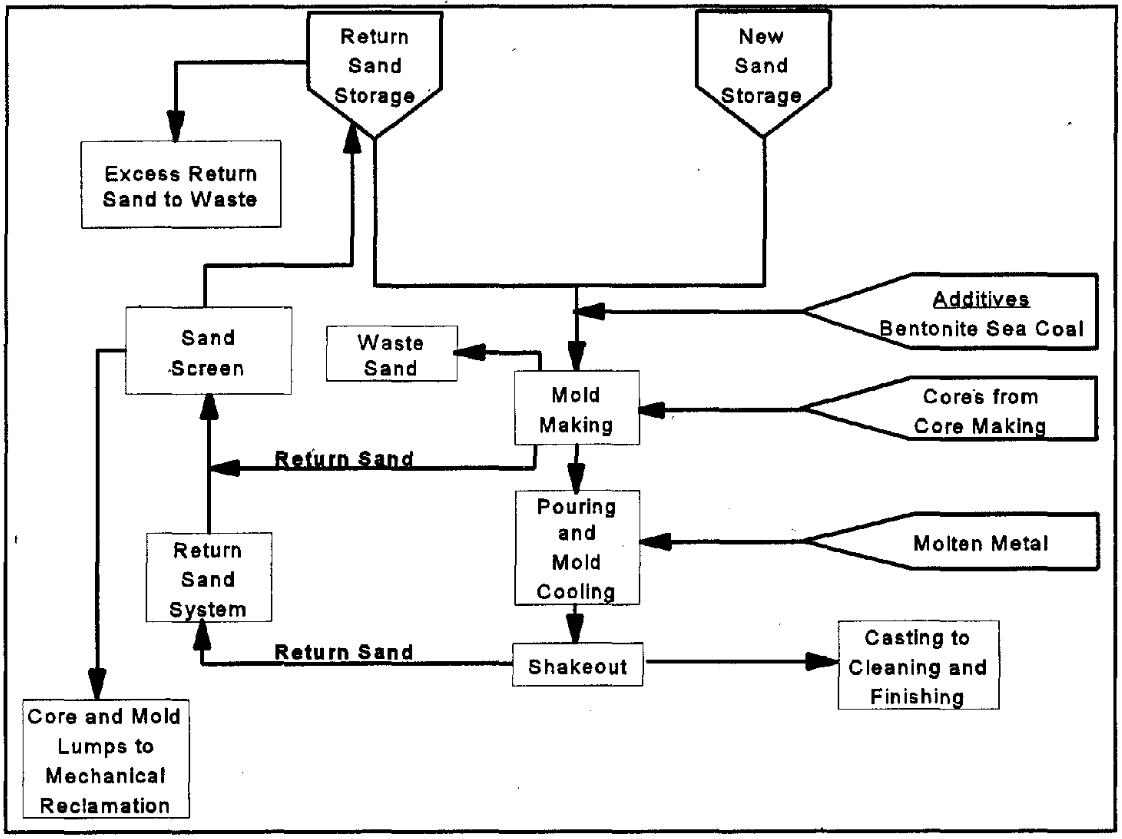

Figure 7-1. Simplified schematic of green sand mold system.

Disposal

Most of the spent foundry sand from green sand operations is landfilled, sometimes being used as a supplemental cover material at landfill sites.

MARKET SOURCES

Foundry sand can be obtained directly from foundries, most of which are located in midwestern states, including Illinois, Wisconsin, Michigan, Ohio, and Pennsylvania.

Foundry sand, prior to use, is a uniformly graded material. The spent material, however, often contains metal from the casting and oversized mold and core material containing partially degraded binder. Spent foundry sand may also contain some leachable contaminants, including heavy metals and phenols that are absorbed by the sand during the molding process and casting operations. Phenols are formed through high-temperature thermal decomposition and rearrangement of organic binders during the metal pouring process.(4) The presence of heavy metals is of greater concern in nonferrous foundry sands generated from nonferrous foundries.(5) Spent foundry sand from brass or bronze foundries, in particular, may contain high concentrations of cadmium, lead, copper, nickel, and zinc.(3)

HIGHWAY USES AND PROCESSING REQUIREMENTS

Asphalt Concrete and Flowable Fill Aggregate

Foundry sand has been used as a substitute for fine aggregate in asphalt paving mixes. It has also been used as a fine aggregate substitute in flowable (or controlled density) fill applications.

Prior to use, spent foundry sand requires crushing or screening to reduce or separate oversized materials that may be present. Stockpiles of sufficient size typically need to be accumulated so that a consistent and uniform product can be produced (i.e., day-to-day variations in the material characteristics can be overcome by blending in a comparatively large stockpile).

Since only small quantities of spent foundry sand are generated at small foundries, it will generally be necessary for these operators to transport their spent sand to a central storage area that receives sand from a group of plants before transferring it to an end user.

Little information is available regarding the amount of foundry sand that is used for purposes other than in-plant reclamation, but spent foundry sand has been used as a fine aggregate substitute in construction applications and as kiln feed in the manufacture of Portland cement.

MATERIAL PROPERTIES

Physical Properties

Typical physical properties of spent foundry sand from green sand systems are listed in Table 7-1.

Table 7-1. Typical physical properties of spent green foundry sand.

Property	Results	Test Method
Specific Gravity(3)	2.39 - 2.55	ASTM D854
Bulk Relative Density, kg/m^3 (lb/ft^3)(7)	2590 (160)	ASTM C48/AASHTO T84
Absorption, %(1,7,3)	0.45	ASTM C128
Moisture Content, %(3)	0.1 - 10.1	ASTM D2216
Clay Lumps and Friable Particles(1,3)	1 - 44	ASTM C142/AASHTO T112
Coefficient of Permeability (cm/sec)(3)	10^{-3} - 10^{-6}	AASHTO T215/ASTM D2434
Plastic limit/plastic index(7)	Nonplastic	AASHTO T90/ASTM D4318

The grain size distribution of spent foundry sand is very uniform, with approximately 85 to 95 percent of the material between 0.6 mm and 0.15 mm (No. 30 and No. 100) sieve sizes. Five to 12 percent of foundry sand can be expected to be smaller than 0.075 mm (No. 200 sieve). The particle shape is typically subangular to rounded. Waste foundry sand gradations have been found to be too fine to satisfy some specifications for fine aggregate.

Spend foundry sand has low absorption and is nonplastic. Reported values of absorption were found to vary widely, which can also be attributed to the presence of binders and additives.(3) The content of organic impurities (particularly from sea coal binder systems) can vary widely and can be quite high. This may preclude its use in applications where organic impurities could be important (e.g., Portland cement concrete aggregate).(4) The specific gravity of foundry sand has been found to vary from 2.39 to 2.55. This variability has been attributed to the variability in fines and additive contents in different samples.(3) In general, foundry sands are dry, with moisture contents less than 2 percent. A large fraction of clay lumps and friable particles have been reported, which are attributed to the lumps associated with the molded sand, which are easily disintegrated in the test procedure.(3) The variation in permeability, listed in Table 7-1, is a direct result of the fraction of fines in the samples collected.

Chemical Properties

Spent foundry sand consists primarily of silica sand, coated with a thin film of burnt carbon, residual binder (bentonite, sea coal, resins) and dust. Table 7-2 lists the chemical composition of a typical sample of spent foundry sand as determined by x-ray fluorescence.

Table 7-2. Foundry sand sample chemical oxide composition, %. (1)

Constituent	Value (%)
SiO_2	87.91
Al_2O_3	4.70
Fe_2O_3	0.94
CaO	0.14
MgO	0.30
SO_3	0.09
Na_2O	0.19
K_2O	0.25
TiO_2	0.15
P_2O_5	0.00
Mn_2O_3	0.02
SrO	0.03
LOI	5.15 (0.45 to 9.47)(1) 2.1 - 12.1(3)
TOTAL	99.87

Silica sand is hydrophilic and consequently attracts water to its surface. This property could lead to moisture-accelerated damage and associated stripping problems in an asphalt pavement. Antistripping additives may be required to counteract such problems.

Depending on the binder and type of metal cast, the pH of spent foundry sand can vary from approximately 4 to 8.(7) It has been reported that some spent foundry sands can be corrosive to metals.(5)

Because of the presence of phenols in foundry sand, there is some concern that precipitation percolating through stockpiles could mobilize leachable fractions, resulting in phenol discharges into surface or ground water supplies. Foundry sand sources and stockpiles must be monitored to assess the need to establish controls for potential phenol discharges.(4,6,7)

Mechanical Properties

Typical mechanical properties of spent foundry sand are listed in Table 7-3. Spent foundry sand has good durability characteristics as measured by low Micro-Deval abrasion(8) and magnesium sulfate soundness loss(9) tests. The Micro-Deval abrasion test is an attrition/abrasion test where a sample of the fine aggregate is placed in a stainless steel jar with water and steel bearings and rotated at 100 rpm for 15 minutes. The percent loss has been determined to correlate very well with magnesium sulfate soundness and other physical properties. Recent studies have reported relatively high soundness loss, which is attributed to samples of bound sand loss and not a breakdown of individual sand particles.(3) The angle of shearing resistance (friction angle) of foundry sand has been reported to be in the range of 33 to 40 degrees, which is comparable to that of conventional sands.(3)

Table 7-3. Typical mechanical properties of spent foundry sand.

Property	Results	Test Method
Micro-Deval Abrasion Loss, %(5)	<2	–
Magnesium Sulfate Soundness Loss, %	5 - 15(1,5) 6 - 47(3)	ASTM C88
Friction Angle (deg)(3)	33 - 40	–
California Bearing Ratio, %(3)	4 - 20	ASTM D1883

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INTRODUCTION

Ferrous spent foundry sand can be used as fine aggregate in hot mix asphalt pavements.(1,2,3) Satisfactory performance has been obtained from hot mix pavements incorporating up to 15 percent clean, spent foundry sand.

Hot mix asphalt pavements with more than 15 percent of clean spent foundry sand content (blended with natural sand) are susceptible to moisture damage due to the hydrophilic nature of the (primarily silica) foundry sand, resulting in stripping of the asphalt cement coating surrounding the aggregate grains, loss of fine aggregate, and accelerated pavement deterioration. The problem can be mitigated by using antistripping additives.

Spent sands from nonferrous foundries and foundry baghouse dust can contain a high concentration of heavy metals that could preclude their use as an aggregate in pavement construction.

PERFORMANCE RECORD

The commercial use of spent foundry sand in the United States is extremely limited. There are no documented field uses of foundry sand in asphalt paving mixes. In an American Foundrymen's Society study of asphalt concrete properties (using 10 percent foundry sand) compared with control mixes (without foundry sand), the results indicated little difference in Marshall design properties (e.g., voids, voids in mineral aggregate, stability, flow, and unit weight).(4) A more recent study was undertaken at Purdue University with samples containing up to 30 percent foundry sand. Increasing foundry sand blends above 15 percent lowered the unit weight, increased the air voids, decreased the flow and stability of the mixes, and reduced the indirect tensile strength (after immersion in a hot water bath), which is indicative of samples that are susceptible to stripping problems.(4)

MATERIAL PROCESSING REQUIREMENTS

Crushing and Screening

It may be necessary to crush and screen the spent foundry sand to reduce the size of any oversize core butts or uncollapsed molds prior to use as aggregate. This is readily accomplished using conventional aggregate processing equipment (closed loop crushing and screening process, equipped with magnetic separator, as necessary).

It is also important that consistency (primarily gradation) be maintained for hot mix asphalt production. Variations between foundries require that spent foundry sands be examined and evaluated on a source-specific basis.

Quality Control

For spent foundry sand to be suitable as a partial replacement for natural fine aggregates in asphalt pavements, it should be free of objectionable materials such as wood, garbage, and metal, which can be introduced at the foundry. Spent foundry sand should also be free of thick coatings of burnt carbon, binders, and mold additives. These constituents can inhibit adhesion of the asphalt cement binder to the foundry sand.

Storage and Blending

Stockpiles of sufficient size should be accumulated so that product uniformity can be achieved. This may necessitate the accumulation of a substantial quantity of spent foundry sand in a central site at a specific foundry or group of foundries before transferring the material to hot mix producers.

To satisfy the gradation requirements for hot mix asphalt fine aggregates (AASHTO M29),(5) the spent foundry sand must be blended with natural sand at the hot mix plant.

ENGINEERING PROPERTIES

Some of the properties of spent foundry sand that are of particular interest when foundry sand is used in asphalt paving applications include particle shape, gradation, durability, and plasticity. With the exception of gradation, clean, processed foundry sands can generally satisfy the physical requirements for hot mix asphalt fine aggregate (AASHTO M29).

<u>Particle Shape</u>: The grain size distribution of spent foundry sand is very uniform, with approximately 85 to 95 percent of the material between 0.6 mm and 0.15 mm (No. 30 and No. 100) sieve sizes. The grains are generally rounded to subangular in shape.

<u>Gradation</u>: The gradation tends to fall within the limits for a poorly graded fine sand that has relatively uniform size (passing 0.3 mm and retained 0.15 mm), with fines content (less than 0.075 mm (No. 200 sieve)) ranging from 5 to 15 percent.

Durability: Spent foundry sands display good durability characteristics with resistance to weathering.(6,7)

Plasticity: Spent foundry sand generated by foundries using green sand molding systems, in which bentonite clay and sea coal are added to the casting, should be examined to ensure that plasticity levels comply with AASHTO requirements for fine aggregates.

Stripping is one of the more critical properties that should be assessed when foundry sand is incorporated into an asphalt mix.

Stripping: Spent foundry sand is composed primarily of silica sand, coated with a thin film of burnt carbon, residual binder (bentonite, sea coal, resins), and dust. The hydrophilic nature of the (primarily silica) foundry sand, however, can result in stripping of the asphalt cement coating surrounding the aggregate grains, with resulting loss of fine aggregate and accelerated pavement deterioration. This problem can be mitigated by limiting the content of spent foundry sand in the mix to 15 percent of the total mass of aggregate or using an antistripping additive.

DESIGN CONSIDERATIONS

Mix Design

Asphalt mixes containing foundry sand can be designed using standard asphalt mix design methods (Marshall, Hveem).

The potential for stripping of asphalt mixes containing spent foundry sand should be assessed in the laboratory as part of the overall mix design. Several tests are available, with the most common including AASHTO T283-85,(8) which compares the tensile strength ratio of wet and dry specimens, and AASHTO T182-84,(9) AASHTO T195-67,(10) or the Immersion Marshall test following the MTO LS-283(11) procedure, which compares the retained Marshall stability and visual appearance of Marshall briquettes before and after immersion in a heated water bath. Stripping resistance can be enhanced by adding hydrated lime or commercially available antistripping additives.

Structural Design

Conventional AASHTO pavement design methods are appropriate for asphalt paving incorporating spent foundry sand as fine aggregate.

CONSTRUCTION PROCEDURES

Material Handling and Storage

The same general methods and equipment used to handle conventional aggregates are applicable for foundry sand.

Foundry sand, which is usually obtained in a dry form, can be stored in covered structures to preserve this condition and reduce energy required for drying. Special measures may be required to control the leachate (containing phenols) from open stockpiles (including temporary stockpiles).(12) The use of an impervious pad (to collect surface moisture or precipitation passing through the stockpile) and subsequent filtration (using an activated carbon filter) of the leachate has proven to be effective (but potentially expensive) in limiting the phenol concentration of the discharge.(6,7)

Mixing, Placing, and Compacting

The same methods and equipment used for conventional hot mix asphalt pavement are applicable to pavements containing spent foundry sand. If it is dry (less than 5 percent moisture), spent foundry sand can be metered directly into a pugmill (batch plants only) or through a recycled asphalt feed (drum plants) where it can be further dried, if necessary, by the already heated conventional aggregates.(13)

The presence of bentonite and organic binder materials can increase the time required for drying and can increase the load on the hot mix plant dust collection system (baghouse). Any coal and organic binders that are present are usually combusted in the process.

The same methods and equipment used for placing and compacting conventional pavements are applicable for pavements incorporating foundry sand.

Quality Control

The same field testing procedures used for conventional hot mix asphalt mixes should be used for mixes containing foundry sand. Mixes should be sampled in accordance with AASHTO T168,(14) and tested for specific gravity in accordance with ASTM D2726(15) and in-place density in accordance with ASTM D2950.(16)

UNRESOLVED ISSUES

There is a need to establish standard methods of assessing the suitability of foundry sand for hot mix asphalt use. The Immersion Marshall test appears to be appropriate for assessing stripping potential.

Additional performance data are required to determine the maximum amount of foundry sand that can be incorporated in hot mix asphalt without deleterious effects.

There is a need to define the potential environmental problems associated with phenol discharges from foundry sand stockpiles, and to determine appropriate treatment strategies, if necessary

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INTRODUCTION

Ferrous spent foundry sand can be used as substitute for natural sand (fine aggregate) in flowable fill.(1,2) Natural sand is a major component of most flowable fill mixes. Spent sands from nonferrous foundries and foundry baghouse dust can contain high concentrations of heavy metals that may preclude their use in flowable fill applications.

Flowable fill or controlled low strength material (CLSM) is generally composed of a mixture of sand, fly ash from coal-fired power plants, a small amount of cement, water, and admixtures. It is defined by ACI Committee 229(3) as a cementitious material that is in a flowable state at the time of placement and that has a specified compressive strength of 1400 kPa (200 lb/in^2) or less at 28 days. This makes it possible for the material to be removed should future excavation be necessary. The applications of flowable fill are numerous and include restoration of utility cuts in county roads, backfilling structures, filling abandoned wells, filling voids under existing pavements, and pipe embedments. (See references 4,5,6,7, and 8.)

The specifications in most jurisdictions for flowable fill materials require that aggregates satisfy ASTM C33.(9) While spent foundry sand may not satisfy the gradation requirements of ASTM C33 for fine aggregates, the uniform, spherical nature of the particles produces a relatively free-flowing mixture.

PERFORMANCE RECORD

There has been limited reported use of spent foundry sand in flowable fills or cementitious applications. It is reportedly being used in flowable fill applications in the Buffalo, New York area.(10) Pennsylvania has reported successful use of foundry sand as a sand substitute in flowable fill. Illinois, however, has tried spent foundry sand and considered such use unsuitable due to poor performance or economics.(11)

MATERIAL PROCESSING REQUIREMENTS

Crushing and Screening

It may be necessary to crush the spent foundry sand to reduce the size of oversize core butts or uncollapsed molds. The spent foundry sand can also be screened and oversize material (from molds and cores that have not completely collapsed) removed.

Quality Control

For spent foundry sand to be suitable as a replacement for fine aggregate in flowable fill, it should be free of objectionable material such as wood, garbage, and metal that can be introduced at the foundry. It should be free of foreign material and thick coatings of burnt carbon, binders, and mold additives that could inhibit cement hydration.

Storage and Blending

Stockpiles of sufficient size should be accumulated and blended so that a consistent gradation can be achieved before transferring the material to ready-mix concrete plants/flowable fill producers.(12) Where it is specified that aggregates must satisfy the requirements of ASTM C33, the spent foundry sand must be blended with natural or other suitable fine aggregate materials to meet gradation requirements. The presence of organics (from some binder systems such as bentonite clay) may exceed ASTM C33 criteria and must therefore be closely monitored.

ENGINEERING PROPERTIES

Some of the engineering properties of spent foundry sand that are of particular interest when foundry sand is used in flowable fill applications include particle shape, gradation, strength characteristics, soundness, deleterious substances, and corrosivity.

Particle Shape: The grain size distribution of spent foundry sand is more uniform and somewhat finer than conventional concrete sand.(13) The fineness of spent foundry sand contributes to good suspension, limiting segregation of flowable fill. The spherical shape of spent foundry sand particles contributes to good flow characteristics. However, increased particle fineness and sphericity also result in lower strength bearing capacity (CBR) of the hardened flowable fill.(14)

Gradation: Spent foundry sand may not satisfy the ASTM C33 gradation requirement for concrete aggregate and, therefore, it may need to be blended with natural sand or other suitable fine aggregate materials to meet gradation requirements.

Strength Characteristics: Although some organic binder materials can interfere with cement hydration, low (rather than high) strength development is in most cases more desirable with flowable fill to permit excavation at a later date. It has been reported that the flowable fill incorporating spent foundry sand aggregates, fly ash, a small quantity of Portland cement, and water readily satisfies specified limited strength criteria.(15)

Soundness: The performance of spent foundry sands in soundness tests depends on the amount of clay binder materials present in the spent foundry sand, the amount of agglomeration of the fines, and the coating on the individual particles. The greater amount of clay binder or agglomeration, or the thicker the coatings, the higher the soundness loss. Regardless, spent foundry sands generally exhibit favorable performance in soundness testing, with soundness losses less than 10 percent (indicative of durable aggregate).(13)

Deleterious Substances: Poorly managed spent foundry sand could contain objectionable materials such as wood, garbage, metal, carbon, and dust as well as large chunks of sand. For use in flowable fill, spent foundry sand must be managed to ensure that the sand is clean and processed to the proper sand size. Foundry sand is often contaminated with organic material and can have an organic content of up to 12 percent.(16,17)

Corrosivity: Depending on the binder and type of metal cast, the pH of spent foundry sand can vary from approximately 4 to 8.(18) It has been reported that some spent foundry sand can be corrosive to metals.(19) Others have indicated that flowable fill mixes containing spent foundry sand are noncorrosive in nature because of the absence of chlorides and high pH values obtained (11.4 to 12.3).(1)

DESIGN CONSIDERATIONS

Mix Design

Flowable fill mixes are usually designed on the basis of compressive strength, generally after 28 days of ambient temperature curing, but sometimes on the basis of longer term (90 days or more) strength. They are designed to have high fluidity during placement (typical slump of 150 mm to

200 mm (6 to 8 inches)) and to develop limited strength (typically between 340 kPa and 1400 kPa (50 and 200 lb/in^2)), which is sufficient to support traffic without settling, yet can be readily excavated.(20)

Many jurisdictions specify the use of fine aggregates conforming to ASTM C33 in flowable fill, which generally precludes using spent foundry sand unless it is blended with natural sand or other suitable materials.

Structural Design

Structural design procedures for flowable fill materials are no different than geotechnical design procedures for conventional earth backfill materials. The procedures are based on using the unit weight and shear strength of the flowable fill to calculate the bearing capacity and lateral pressure of the material under given site conditions.

CONSTRUCTION PROCEDURES

The same methods and equipment used to mix, transport, and place flowable fill made with conventional aggregates may be used for flowable fill incorporating spent foundry sand.

Material Handling and Storage

The same general methods and equipment used to handle conventional aggregates are applicable for foundry sand. Special measures may be required to control the early contact water leachate (containing phenols) from spent foundry sand stockpiles. The construction of an impervious pad (to collect surface moisture or precipitation passing through the stockpile) and subsequent filtration (through an activated carbon filter) of the leachate has reportedly been effective in limiting the phenol concentration of the discharge.(19)

Mixing, Placing, and Compacting

Flowable fill can be produced at a central concrete mixing plant in accordance with ASTM C94(21) and delivered by concrete truck mixers or using a mobile, volumetric mixer for small jobs. It is important that high fluidity (slump greater than 150 mm (6 in)) be maintained to ensure that the flowable fill material entirely fills all voids beneath pavements and around structures and utilities.

Quality Control

Various standard field and laboratory tests for flowable fill mixes are given by AASHTO: T27,(22) ASTM Provisional Standards 28 - Provisional Test Method for Flow Consistency of Controlled Low Strength Materials; and ASTM Provisional Standards 29 - Provisional Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Controlled Low Strength Material.

UNRESOLVED ISSUES

Most existing specifications require that the fine aggregate for flowable fill satisfy ASTM C33. Since foundry sand does not meet the gradation requirements of this standard, there is a need to review gradation requirements and investigate the impact of alternative gradations to permit wider use of spent foundry sand for this application. There also is a need to develop standardized mix design methods for assessing the suitability of foundry sand in flowable fill as well as a need to assess the environmental suitability of spent foundry sand for flowable fill from ferrous and particularly nonferrous foundries.

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ORIGIN

Kiln dusts are fine by-products of Portland cement and lime high-temperature rotary kiln production operations that are captured in the air pollution control dust collection system (e.g., cyclones, electrostatic precipitators, and baghouses).

Cement Kiln Dust

Cement kiln dust (CKD) is a fine powdery material similar in appearance to Portland cement. Fresh cement kiln dusts can be classified as belonging to one of four categories, depending on the kiln process employed and the degree of separation in the dust collection system.(1) There are two types of cement kiln processes: wet-process kilns, which accept feed materials in a slurry form; and dry-process kilns, which accept feed materials in a dry, ground form. In each type of process the dust can be collected in two ways: (1) a portion of the dust can be separated and returned to the kiln from the dust collection system (e.g., cyclone) closest to the kiln, or (2) the total quantity of dust produced can be recycled or discarded. A simplified schematic of a Portland cement manufacturing operation is presented in Figure 8-1.

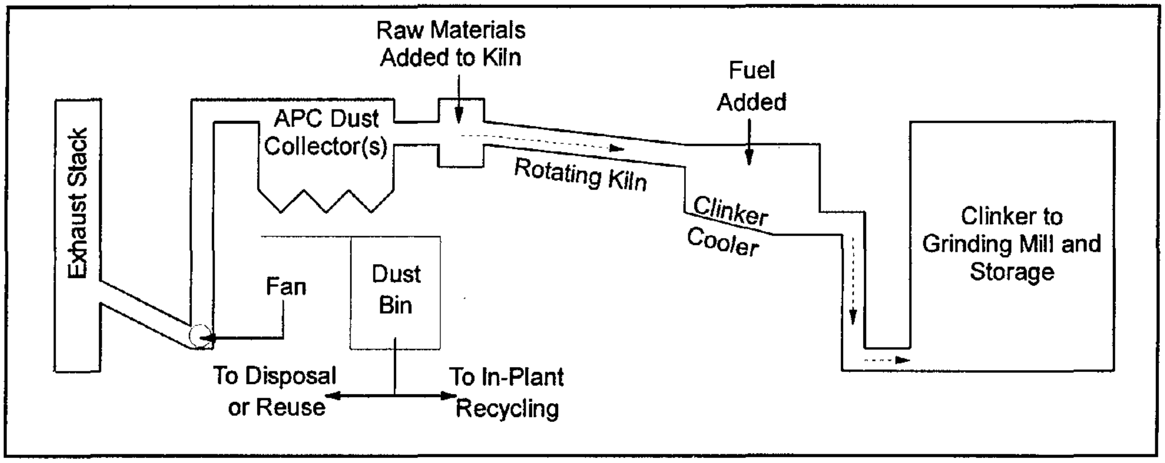

Figure 8-1. Portland cement manufacturing operations.

The chemical and physical characteristics of CKD that is collected for use outside of the cement production facility will depend in great part on the method of dust collection employed at the facility. Free lime can be found in CKD, and its concentration is typically highest in the coarser particles captured closest to the kiln. Finer particles tend to exhibit higher concentrations of sulfates and alkalis. If the coarser particles are not separated out and returned to the kiln, the total dust will be higher in free lime (since it will contain some coarse particles). CKD from wet-process kilns also tends to be lower in calcium content than dust from dry-process kilns.

Approximately 12.9 million metric tons (14.2 million tons) of CKD are produced annually.(2)

Lime Kiln Dust

Lime kiln dust (LKD) is physically similar to cement kiln dust, but chemically quite different. LKD can vary chemically depending on whether high-calcium lime (chemical lime, hydrated lime, quicklime) or dolomitic lime is being manufactured.

Fresh LKD can be divided into two categories based on relative reactivity, which is directly related to free lime and free magnesia content. Free lime and magnesia content are most dependent on whether the feedstock employed is calcitic or dolomitic limestone. LKD with a high free lime content is highly reactive, producing an exothermic reaction upon addition of water. This "quick" LKD is of greatest commercial interest as a direct replacement or substitute for hydrated lime.

Approximately 1.8 to 3.6 million metric tons (2 to 4 million tons) of LKD are generated each year in the United States.(3)

In addition to fresh CKD and LKD production, it is estimated that the total amount of kiln dust currently stockpiled throughout the country exceeds close to 90 million metric tons (100 million tons). These stockpiles are usually located relatively close to the cement and lime manufacturing plants, and vary in age and composition, with exposure to the elements (moisture in particular) reducing the chemical reactivity of the dusts.

CURRENT MANAGEMENT OPTIONS

Recycling

Most of the CKD produced is reused within the cement plant. About 64 percent of the total CKD generated (or about 8.3 million metric tons) is used in this fashion.(2) Approximately 6 percent of the total CKD generated is utilized off-site. The most common beneficial use of CKD is its use as a stabilizing agent for wastes, where its absorptive capacity and alkaline properties can reduce the moisture content, increase the bearing capacity, and provide an alkaline environment for waste materials.

Both cement and lime kiln dusts have been used as stabilizing and solidifying agents in the treatment of soft or wet soils for engineering purposes(4) and for environmental remediation.(5)

Both dusts have also been used as pozzolan initiators,(6) as a pelletized lightweight aggregate material, as a mineral filler in asphalt pavements, and as a fill material in earth embankments.

A significant potential market for CKD and LKD exists for its use as a soil conditioner for agricultural purposes (in lieu of agricultural lime) and as an acid-neutralizing agent in agricultural and water treatment applications. However, at the present time, the EPA is evaluating the possible need to regulate the use of CKD in this application.

In recent years hazardous waste has been used as a fuel in cement kiln operations. The use of waste materials in cement kiln operations has raised concerns regarding the accumulation of heavy metals (e.g., lead, cadmium, and chromium) in CKD generated by plants that use these alternative materials.(2) In addition, runoff and precipitation that contact CKD storage piles have exhibited pH levels above 12.5, which can be highly corrosive.(7) The EPA has expressed concern over uncontrolled transport, storage, and disposal of large volumes of CKD (in uncovered and unlined piles), which are easily removed by wind and eroded by water.

In a recent regulatory determination, the EPA committed to the development of revised standards for managing CKD.(7) In this regulatory determination, EPA stated, with respect to beneficial uses, that "for most off-site uses (e.g., waste stabilization or certain construction uses) EPA's current record indicates that there are no significant risks." This would not preclude the need to examine the chemical quality of CKD prior to its use.

Disposal

At the present time, approximately 80 percent of the surplus CKD remaining after reuse in cement manufacturing is stockpiled or landfilled.(2) Most of the LKD generated in the United States is currently disposed of in stockpiles or landfills.(3)

MARKET SOURCES

Kiln dusts may be obtained directly from Portland cement or hydrated lime producers. Waste management firms retained by the manufacturers may also supply cement and lime kiln dusts. The specific characteristics of the CKD and LKD vary from plant to plant depending on the feedstock employed at the cement or lime production plant, the major products being manufactured, kiln design and operation, fuel type, and the type of dust control/collection systems employed.

The primary value of cement and lime kiln dusts is their cementitious properties. Depending on the concentration of hydratable oxides present in the CKD and LKD, primarily unreacted or free lime (CaO) and free magnesia (MgO) respectively, cement kiln dust and lime kiln dust can be highly cementitious.

Fresh CKD and LKD are generally difficult to handle in bulk because of their fine, dry, powdery nature and caustic characteristics. The addition of water to mitigate blowing and dusting problems during transport is common, but this practice causes premature hydration of the free lime or magnesia and significantly reduces the cementitious potential of the CKD or LKD. Where the CKD or LKD must be kept dry to preserve its cementitious potential, it must be handled in a fashion that is similar to conventional cement or lime (pneumatically loaded into and unloaded from cement tanker trucks and stored in silos).

The processing of stockpiled CKD and LKD can be difficult. Typically, very large, aboveground stockpiles or backfilled quarries (source of raw product for cement manufacture) are involved, representing many years of cement or lime production. The surface of the stockpile or fill site usually crusts over and becomes hard, while the interior of the stockpile can stay relatively loose and can contain some unhydrated material even after many years if exposure to moisture is limited. Processing of hardened stockpiled kiln dusts requires crushing and screening equipment to remove oversize pieces as well as any litter or garbage (wood, etc.) that may have become mixed with the kiln dusts.

HIGHWAY USES AND PROCESSING REQUIREMENTS

Asphalt Concrete Mineral Filler

CKD and LKD have been used as mineral filler in asphalt concrete mixes. The blending of CKD into the asphalt cement binder prior to incorporation with the hot mix aggregate results in a binder (mastic) that can significantly reduce asphalt cement requirements (between 15 and 25 percent by volume).(8) Further, the lime components of the CKD and LKD can assist in promoting stripping resistance (preventing moisture-related damage resulting from the separation of the asphalt cement film from the aggregate at its interface in the presence of moisture that is most common in siliceous aggregates). In this application, these dusts can be used to replace hydrated lime or liquid antistripping agents.

CKD can also be used as a replacement for Portland cement or hydrated lime in slurry seals (mix of fine aggregate and emulsified asphalt). Slurry seal mixes with 2 percent kiln dust prepared in the laboratory, using a stripping fine aggregate gave excellent results in abrasion resistance testing.(9)

Asphalt Concrete Aggregate

CKD and LKD can also be agglomerated or pelletized to produce an artificial aggregate for special applications. In Japan an oil-absorbing artificial aggregate is reportedly manufactured using CKD that is used to improve the rutting resistance of asphalt concrete pavements by absorbing the lighter fractions of excess asphalt cement binder during hot weather.

Asphalt Cement Modifier

CKD can be added to asphalt binder to produce a low ductile mastic asphalt. Mastic asphalt is a mixture of asphalt binder and fine mineral material. When mastic asphalt is produced using CKD mixed 50/50 with an asphalt cement binder, a potential exists for a relatively large volume replacement of asphalt cement (between 15 and 25 percent by volume). The European use of mastic asphalts, with low ductility, for bridge deck waterproofing and protection is well documented, and this could represent a potential application for kiln dusts in the United States.(10,11,12)

Stabilized Base or Flowable Fill Cementitious Materials

CKD can be used as a cementitious material or a pozzolan activator in stabilized base or flowable fill applications. LKD has potential for use as a pozzolan activator in each respective application. As a cementitious material, CKD can replace or be used in combination with Portland cement. As a pozzolan activator, both CKD and LKD can replace or be used in combination with Portland cement or hydrated lime.

MATERIAL PROPERTIES

Physical Properties

CKD and LKD are fine, powdery materials of relatively uniform size. Table 8-1 lists some typical physical properties of both cement and lime kiln dusts.

Approximately 75 percent of the kiln dust particles are finer than 0.030 mm (No. 450 sieve). The fineness of kiln dust, as Portland cement, can be determined using the Blaine air permeability apparatus in accordance with ASTM C204.(13)

The maximum particle size of most CKD is about 0.30 mm (No. 50 sieve), with the Blaine fineness ranging from about 4600 (coarser) to 14000 (finer) cm^2/g.(1) LKD is generally somewhat more coarse than CKD, having a top size of about 2 mm (No. 10 sieve) and Blaine fineness ranging between about 1300 and 10000 cm^2/g. In comparison, the Blaine fineness of Type I Portland cement is about 3500 to 3800 cm^2/g.(14)

The specific gravity of CKD is typically in the range of 2.6 to 2.8, less than that of Portland cement (specific gravity of 3.15). LKD exhibits specific gravities ranging from 2.6 to 3.0.(1)

Table 8-1. Typical range of physical properties of cement and lime kiln dusts.(7)

Property	Value	
	Cement Kiln Dust	Lime Kiln Dust
Gradation 75% passing	0.030 mm (No. 450 sieve)	0.030 mm (No. 450 sieve)
Maximum Particle Size	0.300 mm (No. 50 sieve)	2 mm (No. 10 sieve)
Specific Surface (cm^2/g)	4600 - 14,000	1300 - 10,000
Specific Gravity	2.6 - 2.8	2.6 - 3.0

Chemical Properties

Chemically, CKD has a composition similar to conventional Portland cement. The principal constituents are compounds of lime, iron, silica and alumina. Table 8-2 lists typical compositions for fresh and stockpiled CKD and LKD.

The free lime content of LKD can be significantly higher than that of CKD (up to about 40 percent), with calcium and magnesium carbonates as the principal mineral constituents. There is very little, if any, free lime or free magnesia content in stockpiled CKD and LKD that has been exposed to the environment for long periods.(1)

The pH of CKD and LKD water mixtures is typically about 12. Both materials contain significant alkalis, and consequently are considered to be caustic. Due to the caustic nature of CKD and LKD, some corrosion of metals (e.g., aluminum) that come in direct contact with CKD and LKD may occur.

Trace constituents in CKD (including certain trace metals such as cadmium, lead, and selenium, and radionuclides) are generally found in concentrations less than 0.05 percent by weight.

Because some of these constituents are potentially toxic at low concentrations, it is important to assess their levels (and mobility or leachability) in CKD before considering its use.(7)

Table 8-2. Typical chemical compositions of cement kiln dust and lime kiln dust.(1)

Parameter	Cement Kiln Dust			Lime Kiln Dust		
	Fresh	Stockpiled		Fresh		Stockpiled
		Sample 1	Sample 2	High*	Low*	
CaO	40.5	31.4	44.2	54.5	31.2	31.2
Free Lime	4.4	0.0	0.0	26.4	5.1	0.0
SiO_2	14.5	11.7	11.9	9.94	2.46	1.74
Al_2O_3	4.10	3.18	3.24	4.16	0.74	0.71
MgO	1.55	0.97	1.73	0.49	23.5	23.3
Na_2O	0.44	0.13	0.27	0.03	0.00	0.05
K_2O	4.66	1.65	2.92	0.22	0.09	0.03
Fe_2O_3	2.00	2.16	1.45	1.98	0.94	1.3
SO_3	6.50	8.24	2.40	7.97	2.80	3.5
Loss On Ignition, 105°C	22.9	40.4	30.2	14.2	37.4	27.9

* Two types of lime kiln dust were classified in the reported data (high reactivity and low reactivity) on the basis of the release of heat and rise in temperature when placed in solution.

Mechanical Properties

CKD has a loose density of only about 480 kg/m^3 (30 lb/ft^3), but can be compacted to about 1350 to 1500 kg/m^3 (85 to 95 lb/ft^3) using conventional soils compaction practices.(15)

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INTRODUCTION

Both fresh cement kiln dust (CKD) and lime kiln dust (LKD) can be used as mineral filler in hot mix asphalt paving.(1) Hot mix asphalt surface course mixes containing low addition levels of either fresh CKD or LKD as mineral filler (approximately 5 percent by weight of aggregate) reportedly exhibit mix properties comparable to mixes containing natural filler such as hydrated lime and stone dust. Gradation, organic impurities, and plasticity requirements normally associated with mineral filler specification requirements can usually be met without difficulty.

PERFORMANCE RECORD

Although research has shown the feasibility of using CKD, and especially LKD, in lieu of commercial hydrated lime as a mineral filler, few agencies have been involved in testing or field trials.(2,3) Three states have reported some research on the use of CKD for use as mineral filler (Arizona, New York, and Utah), and only one state (Utah) has investigated the use of LKD for this application.(4)

Some use of CKD as a mineral filler in highway asphalt concrete has been reported in Italy where both the performance and Marshall properties of asphalt mixes with CKD filler were reported to be good, at addition rates that are comparable to that for commercial hydrated lime (about 6 percent).(1)

The lime components of the CKD and LKD can assist in promoting stripping resistance. In this application, these dusts can be used to replace hydrated lime or liquid antistripping agents.(2,3)

MATERIAL PROCESSING REQUIREMENTS

Screening

The specification requirements for mineral fillers (AASHTO M17),(5) are shown in Table 8-3. The grading requirements for mineral fillers are such that CKD can, with minimal screening, readily comply with the specification requirements. Some LKD can be somewhat coarse, which will necessitate screening to remove oversize particles.

Storage

Because only fresh, dry kiln dust should be used, the CKD and LKD must be stored in silos or cement trucks. When stored for extended periods in silos, kiln dusts may have a tendency to

Table 8-3. AASHTO M17 specification requirements for mineral filler for use in bituminous paving mixtures.

Particle Sizing		Organic Impurities	Plasticity Index
Sieve Size	Percent Passing		
600 μm (No. 30)	100	Mineral filler must be free from any organic impurities	Mineral filler must have plasticity index not greater than 4
300 μm (No. 50)	95 - 100		
75 μm (No. 200)	70 - 100		

clump or bridge together at the silo feed opening, due to their fine nature. Consequently, bins or silos should be equipped with suitable vibration devices at the feed opening to mitigate this potential problem.

ENGINEERING PROPERTIES

Some of the properties of kiln dust that are of particular interest when kiln dust is used as a mineral filler in asphalt paving applications include particle size and specific gravity.

Particle Size: The maximum particle size of most kiln dusts is about 0.3 mm (No. 50 sieve), which conforms to mineral filler top size requirements outlined in AASHTO M17. Commercial kiln dusts are highly angular. The Blaine fineness(6) ranges from about 4600 (coarser) cm^2/g to 14000 (finer) cm^2/g.(7) LKD is generally somewhat more coarse than cement kiln dusts, having a top size of about 2 mm (No. 10 sieve) and Blaine fineness ranging between about 1300 and 10000 cm^2/g.

Specific Gravity: The specific gravity of CKD is typically in the range of 2.6 to 2.8. LKD exhibits specific gravities in the range of 2.6 to 3.0.(7)

Some of the properties of the asphalt mix that are of interest when kiln dusts are used as a mineral filler are mix durability and binder properties.

Durability: CKD fillers have been observed to increase the durability of hot mix asphalt, but not to the same extent as hydrated lime (due to the lower free lime content of CKD). CKD is not very effective in reducing moisture-related damage (stripping) in asphalt concrete mixes, but

LKD (especially highly reactive LKD) can provide benefits similar to those of commercial hydrated lime.(3)

Binder Properties: At high addition levels, CKD acts as an extender of the asphalt cement binder, allowing up to about 25 percent by volume replacement of the asphalt cement component. CKD mineral filler results in increased stability and stiffening (lower penetration, higher softening point, and higher kinematic viscosity).(8)

DESIGN CONSIDERATIONS

Mix Design

Asphalt mixes containing kiln dusts can be designed using standard laboratory procedures. The mineral filler should satisfy the requirements of AASHTO M17.(6) Immersion-compression tests should be conducted to supplement Marshall mix design testing to determine the moisture sensitivity of paving mixtures containing different types and concentrations of mineral fillers.(9)

Structural Design

Conventional AASHTO pavement structural design methods are appropriate for asphalt concrete incorporating kiln dust as mineral filler.

CONSTRUCTION PROCEDURES

There are no additional or special construction procedures involved for the use of CKD or LKD beyond those required for conventional mineral fillers.

Material Handling

Kiln dusts for use as mineral filler can be precoated with asphalt emulsion (approximately 10 percent by mass) to facilitate handling and transportation. The emulsion value is largely recovered when incorporated in hot mix asphalt, but the cost nevertheless increases without apparent improvement in mix properties.

Placing and Compacting

The same methods and equipment used for conventional pavements are applicable to asphalt pavements containing kiln dusts.

Quality Control

The same field testing procedures used for conventional hot mix asphalt mixes should be used for mixes containing kiln dusts. Mixes should be sampled in accordance with AASHTO T168,(10) and tested for specific gravity in accordance with ASTM D2726,(11) and in-place density in accordance with ASTM D2950.(12)

UNRESOLVED ISSUES

Some kiln dust sources have been used successfully as mineral filler in asphalt paving applications; however, there are not adequate data on the different properties of specific sources of kiln dust and its economic viability for use as a mineral filler.

The addition of larger quantities of kiln dust to the binder (stone mastic asphalt) and its properties should be investigated to assess its potential for use in special applications.

The effectiveness CKD and LKD as antistripping agents should be evaluated at different rates of addition.

The environmental properties of CKD and LKD should be better defined and management practices delineated to ensure that CKD and LKD are managed in an environmentally acceptable manner.

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INTRODUCTION

Both cement kiln dust (CKD) and lime kiln dust (LKD) can be used as activators in pozzolanic stabilized base mixtures. Depending on its reactivity, CKD may have potential for use as the sole cementitious material in stabilized base mixtures. Most work with kiln dusts, however, has involved combinations of kiln dusts and coal fly ash as the cementitious component of the mixture. The strength of kiln dust-fly ash-aggregate base and subbase materials is dependent on three factors: the kiln dust, the coal fly ash, and the aggregate. Either pozzolanic or self-cementing fly ash can be used as part of stabilized base (PSB) mixtures, although precautions may be necessary when using a self-cementing fly ash. With self-cementing fly ashes, no activators are needed.

PERFORMANCE RECORD

There is no widespread commercial use of kiln dusts in stabilized base mixtures in the United States today. Only four states are reported to have research data on the use of CKD for stabilized base.(1) Research conducted in Kentucky found that LKD performed better in stabilized base applications than CKD.(2) Trial LKD sections constructed in Ohio and tested over a period of 6 months exhibited no cracking or surface damage, and deflections were observed to decrease with time as the pavement cured.

In the Ohio project, six test sections were constructed in November 1997 as part of a research study by the University of Toledo. The fly ash/CKD/Portland cement blends (percent by mass dry ingredients) utilized in this study were: 6/6/0, 8/8/0, 10/10/0, 12/12/0, 8/8/0.5, and 8/8/1. The total traffic during this period was 25,820 equivalent 8,165 kg (18,000 lb) single-axle loads. CKD sections were reported to exhibit dimensional (volumetric) stability problems, which were attributed to the presence of sulfates and alkalis in the dust.

MATERIAL PROCESSING REQUIREMENTS

Material Handling

Where possible, aged stockpiled CKD and LKD should not be used (due to hydration and the loss of reactivity) as a component of stabilized highway base material unless conditioned by the addition of commercial lime or other caustic material to enhance short-term strength development.(3)

If fresh kiln dust is being used, it must be stored in enclosed bins or silos to keep out moisture and prevent dusting. CKD and LKD can also be used with fly ash, provided the dust is conditioned with moderate amounts of water. The use of moisture-conditioned kiln dust (to suppress dusting) and fly ash allows greater quantities of both materials to be set aside for future use without the need for enclosed storage. Such moisture conditioning will, however, cause full or partial hydration of the available free lime in the dust that may necessitate the later addition of a commercial hydrated lime to improve early strength development.

ENGINEERING PROPERTIES

The properties of kiln dusts that are of particular interest when kiln dusts are used in stabilized base applications are particle size and specific gravity.

Particle Size: Maximum particle size of most kiln dusts is about 0.3 mm. According to AASHTO T153-86(4) the Blaine fineness ranges from about 4600 (coarser) to 14000 (finer) cm^2/g.(3) LKD is generally somewhat more coarse than CKD, having a top size of about 2 mm (No. 10 sieve) and Blaine fineness ranging between about 1300 and 10000 cm^2/g.

Specific Gravity: The specific gravity of CKD is typically in the range of 2.6 to 2.8, similar to Portland cement. LKD exhibits specific gravities in the order of 2.6 to 3.0.(3)

Kiln dusts have been used, primarily as a pozzolanic activator, in kiln dust-fly ash-aggregate base mixtures. Some of the properties of these mixtures that are of interest include strength, durability, volume stability, and autogenous healing properties. These properties are dependent on the properties of the three major components: the kiln dust, the fly ash, and the aggregate.

Strength: Kiln dust-fly ash stabilized base mixtures containing dolomitic limestone aggregates generally exhibit higher densities and compressive strengths than siliceous aggregate blends. Similarly, the strength of the mixtures will be somewhat dependent upon the aggregate shape (higher strength with angular crushed aggregates).

The effect of fly ash on strength development of kiln dust-fly ash-aggregate mixes depends on the type of fly ash used in the mix. Table 8-4 lists typical 7-day compressive strength results that were achieved for kiln dust-fly ash-aggregate mixes.(3) Mixes employing self-cementing fly ash tend to have higher 7-day strengths than those with pozzolanic fly ash.

Table 8-4. Compressive strength of kiln dust-fly ash-aggregate mixes.

Kiln Dusts /Fly Ash Mixes	Seven-Day Compressive Strength
Kiln Dusts with Class C fly ash	8 to 14 MPa (1200 to 2000 lb/in^2)
Kiln Dusts with Class F fly ash	5.5 to 8 MPa (800 to 1200 lb/in^2)

Table 8-5 presents a listing of kiln dust-fly ash-aggregate mixes test results for splitting tensile strength and resilient modulus versus comparative stabilized base mixes using commercial lime.(3)

Table 8-5. Splitting tensile strength and resilient modulus of kiln dust-fly ash-aggregate mixes.

Kiln Dust-Fly Ash-Aggregate Mixes	Splitting Tensile Strength	Resilient Modulus (Modulus of Rupture)
Cement Kiln Dust-Fly Ash (Class F) - Aggregate Mixes	1.5 to 3 MPa (200 to 400 lb/in^2)	about 17000 MPa (2.5 x 10^6 lb/in^2)
Comparative Mixes Using Commercial Lime-Fly Ash-Aggregate Mixes	–	13100 MPa (1.9 x 10^6 lb/in^2)
Mixtures Involving Lime Kiln Dusts	1.5 to 2 MPa (200 to 300 lb/in^2)	–
Comparative Mixes Using Commercial Lime	1.5 MPa (210 lb/in^2)	1.5 MPa (210 lb/in^2)

Durability: The durability of kiln dust-fly ash-aggregate mixtures assessed using the AASHTO T136(5) procedure tends to be very good, with freeze-thaw losses of 2 percent or less measured.(3) This compares favorably with conventional lime-fly ash-aggregate mixes.

Volume Stability: Most kiln dust-fly ash-aggregate mixtures are dimensionally stable (no volumetric expansion) over long periods of time, and again compare favorably to conventional lime-fly ash-aggregate mixtures. CKD that is high in sulfates and alkalis and LKD that has a high free lime content tend to exhibit poorer dimensional stability.(3)

Autogenous Healing: Kiln dust-fly ash-aggregate mixtures in field performance demonstrate autogenous healing properties, although not to the same extent as commercial lime-fly ash-aggregate blends. However, kiln dust systems re-cement across crack boundaries and regain a significant portion of their initial compressive strength.(3)

Chemical Composition: CKD has lower free lime content (approximately 4.4 percent) compared to LKD which can be as high as 40 percent.(6) The pH of water in contact with CKD and LKD mixtures is typically about 12. Due to its relatively high pH, some corrosion of metals (e.g., aluminum) in direct contact with CKD and LKD may occur.

DESIGN CONSIDERATIONS

Mix Design

Mix designs for kiln dust-fly ash-aggregate mixtures for stabilized base should follow similar mix design procedures that have been recommended for lime-fly ash-aggregate mixtures.(3,7) The moisture-density relations of soil cement/stabilized base mixtures are determined using the AASHTO T134 method, (8) with the durability of the mixtures evaluated using the AASHTO T135 wetting and drying test(9) and AASHTO T136 freezing and thawing test.(5)

The suitability of the kiln dust for stabilized base use should be established by a laboratory prescreening test of trial mixes. Due to the difference in free lime content between LKD and CKD, for CKD, a kiln dust:fly ash ratio between 2:1 and 1:1 has been recommended. For LKD, a kiln dust:fly ash ratio between 1:1 and 1:2 has been recommended.(3)

Test specimens should be prepared in accordance with ASTM C593(10). A seven-day compressive strength of 2760 kPa (400 lb/in^2) is considered to be the minimum value for acceptance of the kiln dust with Class F fly ash and 4140 kPa (600 lb/in^2) if Class C fly ash is used.

It is important to maintain a condition of excess moisture for highly reactive LKD and CKD to permit complete hydration of any free lime. A separate slaking test can be completed in advance to estimate the range of slaking water required.

After determining the optimum moisture content for molding, specimens should be prepared and tested for compressive strength, durability (vacuum saturation method as per ASTM C593(10) and freeze-thaw test in accordance with AASHTO T136,(5)) and volume stability (autoclave expansion test (AASHTO T107)(11) or mortar bar expansion test (AASHTO M210).(12) At least three kiln dust-fly ash proportions should be tested in compression to determine the optimal mix for durability and volume stability testing. High-strength mixes may not require durability testing.

Structural Design

Structural design procedures for stabilized base containing kiln dusts are the same as design procedures for conventional stabilized base materials.

CONSTRUCTION PROCEDURES

Material Handling and Storage

Fresh CKD and LKD are generally difficult to handle in bulk because of their fine, dry powdery nature and caustic characteristics. The addition of water to mitigate blowing and dusting problems during transport is common, but this practice causes hydration of the free lime or magnesia and significantly reduces the cementitious potential of the CKD or LKD. Where the CKD or LKD must be kept dry to preserve its cementitious potential, it must be handled in a similar fashion to conventional cement or lime - pneumatically loaded and unloaded from cement tanker trucks and stored in silos.

Kiln dust-fly ash mixtures produced using self-cementing fly ash must handled somewhat differently than mixes with pozzolanic fly ash because self-cementing fly ash mixtures (especially those high in free lime) set up much more rapidly when exposed to water.

Due to the fine nature of kiln dusts, they may have a tendency to clump or bridge together at the feed opening when stored in silos. Consequently, bins or silos should be equipped with suitable vibration devices at the feed opening to mitigate this problem.

Mixing, Placing and Compacting

Kiln dust-fly ash-aggregate mixtures are mixed and placed in uniform lifts and compacted using conventional construction equipment. The mixtures must be placed and compacted continuously and cannot be stockpiled for more than a couple of hours, after which time they will set.

Quality Control

The same test procedures used for conventional aggregate base courses should be used for mixes containing kiln dusts. Various field and laboratory tests for compacted density and field measurement of compaction are given by AASHTO test methods T134,(8) T191,(13) T205,(14) and T238.(15)

UNRESOLVED ISSUES

There is a need for additional research to assess the suitability of using LKD and particularly CKD as a pozzolan activator in stabilized base applications. Specifications are required to define both the physical and chemical requirements needed to ensure acceptable field performance.

The environmental properties of CKD and LKD should be better defined and management practices delineated to ensure that CKD and LKD are managed in an environmentally acceptable manner.

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ORIGIN

Mineral processing wastes are referred to in the Resource Conservation and Recovery Act (RCRA) as wastes that are generated during the extraction and beneficiation of ores and minerals. These wastes can be subdivided into a number of categories: waste rock, mill tailings, coal refuse, wash slimes, and spent oil shale. The mining and processing of mineral ores results in the production of large quantities of residual wastes that are for the most part earth- or rock-like in nature.

It is estimated that the mining and processing of mineral ores generate approximately 1.6 billion metric tons (1.8 billion tons) of mineral processing waste each year in the United States.(1) Mineral processing wastes account for nearly half of all the solid waste that is generated each year in the United States. Accumulations of mineral wastes from decades of past mining activities probably account for at least 50 billion metric tons (55 billion tons) of material.(2) Although many sources of mining activity are located in remote areas, nearly every state has significant quantities of mineral processing wastes.

Waste Rock

Large amounts of waste rock are produced from surface mining operations, such as open-pit copper, phosphate, uranium, iron, and taconite mines. Small amounts are generated from underground mining. Waste rock generally consists of coarse, crushed, or blocky material covering a range of sizes, from very large boulders or blocks to fine sand-size particles and dust. Waste rock is typically removed during mining operations along with overburden and often has little or no practical mineral value. Types of rock included are igneous (granite, rhyolite, quartz, etc.), metamorphic (taconite, schist, hornblende, etc.) and sedimentary (dolomite, limestone, sandstone, oil shale, etc.). It is estimated that approximately 0.9 billion metric tons (1 billion tons) of waste rock are generated each year in the United States.(1)

Mill Tailings

Mill tailings consist predominantly of extremely fine particles that are rejected from the grinding, screening, or processing of the raw material. They are generally uniform in character and size and usually consist of hard, angular siliceous particles with a high percentage of fines. Typically, mill tailings range from sand to silt-clay in particle size (40 to 90 percent passing a 0.075 mm (No. 200) sieve), depending on the degree of processing needed to recover the ore.

The basic mineral processing techniques involved in the milling or concentrating of ore are crushing, then separation of the ore from the impurities.(3) Separation can be accomplished by one or more of the following methods: media separation, gravity separation, froth flotation, or magnetic separation.(4,5,6)

About 450 million metric tons (500 million tons) per year(1) of mill tailings are generated from copper, iron, taconite, lead, and zinc ore concentration processes and uranium refining, as well as other ores, such as barite, feldspar, gold, molybdenum, nickel, and silver. Mill tailings are typically slurried into large impoundments, where they gradually become partially dewatered.

Coal Refuse

Coal refuse is the reject material that is produced during the preparation and washing of coal. Coal naturally occurs interbedded within sedimentary deposits, and the reject material consists of varying amounts of slate, shale, sandstone, siltstone, and clay minerals, which occur within or adjacent to the coal seam, as well as some coal that is not separated during processing.

Various mineral processing techniques are used to separate the coal from the unwanted foreign matter. The equipment most frequently used in these plants is designed to separate the coal from reject materials, and incorporates methods that make use of the difference in specific gravity between the coal and host rock. Most of the coal that is cleaned is deep-mined bituminous coal. The reject material is in the form of either coarse refuse or fine refuse.

Coarse coal refuse can vary in size from approximately 100 mm (4 in) to 2 mm (No. 10 sieve). The refuse is discharged from preparation plants by conveyor or into trucks, where it is taken and placed into large banks or stockpiles. Fine coal refuse is less than 2 mm (No. 10 sieve) and is usually discarded in slurry form. Approximately 75 percent of coal refuse is coarse and 25 percent is fine. Coarse coal refuse is referred to as colliery spoil in the United Kingdom.

Some 109 million metric tons (120 million tons) of coal refuse are generated each year in the United States. There are more than 600 coal preparation plants located in 21 coal-producing states. The largest amounts of coal refuse can be found in Kentucky, West Virginia, Pennsylvania, Illinois, Virginia, Ohio, and Delaware.(1) As the annual production of coal continues to increase, it is expected that the amount of coal refuse generated will also increase.

Wash Slimes

Wash slimes are by-products of phosphate and aluminum production. These wastes are generated from processes in which large volumes of water are used, resulting in slurries having low solids content and fines in suspension. They generally contain significant amounts of water, even after prolonged periods of drying.(7) In contrast, tailings and fine coal refuse, which are initially disposed of as slurries, ultimately dry out and become solid or semi-solid materials. Approximately 90 million metric tons (100 millions tons) of phosphate slimes (wet) and 4.5 million metric tons (5 million tons) of alumina mud (wet) are generated every year in the United States. These reject materials are stored in large holding ponds. Because of the difficulty encountered in drying, there are no practical known uses for wash slimes.

Spent Oil Shale

Oil shale is mined as a source of recoverable oil. Spent oil shale is the waste by-product remaining after the extraction of oil. It is a black residue generated when oil shale is retorted (vaporized and distilled) to produce an organic oil-bearing substance called kerogen. Spent oil shale can range in size from very fine particles, smaller than 0.075 mm (No. 200 sieve), to large chunks, up to 230 mm (9 in) or more in diameter. The coarse spent oil shale resembles waste rock because of its large particle size. The material, when crushed to a maximum size of 19.0 mm (3/4 inch), can be characterized as a relatively dense, well-graded aggregate.(8)

The oil shale industry in the United States initially developed in the early 1970's primarily in northwest Colorado with a series of pilot retorting plants that operated for a number of years. Because of unfavorable economics and a lack of sustained government support, the commercial oil shale industry has never developed. Consequently, there is little or no current production of oil shale, and the only spent oil shale available is from the pilot plant operations, which have since been suspended.

Additional information on the production, location, quantities, and characteristics of various types of mineral processing wastes can be obtained from:

National Mining Association
1130 Seventeenth Street, N.W.
8th Floor
Washington, D.C. 20036

CURRENT MANAGEMENT OPTIONS

Recycling

Although many sources of mineral processing wastes are remotely located, large quantities of these materials have historically been used as highway construction materials whenever it has been economical and appropriate to do so. At least 34 different states have reportedly made some use of one or more types of mineral processing wastes for highway construction purposes.(1)

The mining industry has traditionally made use of its own waste materials, either by reprocessing to recover additional minerals as economic conditions become more favorable, or by using them for internal construction purposes. It is regarded as standard practice in the North American mining industry to utilize mine waste materials in the construction of dikes, impoundments, and haul roads on the mining property, and in mine rehabilitation such as cemented mine backfill.

Nevertheless, internal usage of mining and mineral processing wastes consumes only a small percentage of the millions of tons of such wastes that continue to be generated every year.(8) Many mineral processing waste materials have limited potential for use as aggregates because of their fineness, high impurity content, trace metal leachability, propensity for acid generation, and/or remote location (i.e., away from aggregate markets). However, when the location and material property characteristics are favorable, some sources of waste rock or coarse mill tailings may be suitable for use as granular base/subbase, railroad ballast, Portland cement concrete aggregate, asphalt aggregate, flowable fill aggregate or fill, and engineered fill or embankment.

The EPA is presently in the process of assessing the regulatory status of several mineral processing wastes that could pose environmental problems if not managed in an appropriate manner. These evaluations could affect the feasibility of using these materials in beneficial use applications.(9)

Coarse coal refuse has been successfully used for the construction of highway embankments in both the United States and Great Britain. Coarse coal refuse has also been blended with fly ash and used in a number of stabilized road base installations. Burnt coarse refuse (often referred to as red dog because of its reddish color) has also been used as an unbound aggregate for shoulders and secondary roads. Fine coal refuse (culm or gob) has been recovered for reuse as fuel and is being burned in many cogeneration facilities now operating in the United States.

Because of the low solids content and associated handling difficulties, no practical uses have as yet been found for wash slime materials.(10)

Disposal

The processing of ores typically involves grinding and the addition of water and chemicals in the ore treatment refining plant, with a large portion of the resulting waste leaving the plant in the form of a slurry. Usually this slurry is impounded to permit settling of the solids, with any free water accumulated in the pond pumped back to the plant or allowed to discharge from the pond to an adjacent water course. Other waste rock (gangue) excavated from the ore body, and any coarse wastes separated during processing are stored in waste piles or in the base of tailings dam embankments.(11,12) By far, the major fraction of mining waste such as waste rock is disposed of in heaps (or piles) at the source.

Coarse coal refuse is typically removed from the preparation plant and disposed of in large piles or banks. Such deposits of refuse are sometimes referred to as carbon banks (anthracite) or gob piles (bituminous). Sometimes, refuse in these banks or piles can ignite and burn because of spontaneous combustion.

MARKET SOURCES

Mineral processing wastes are available from mining and mineral processing operations, most of which are located near the mine source and operated by mining companies. The quality of mineral processing wastes can vary widely and is highly dependent on the specific source. To properly assess these issues, each source of mineral processing waste must be separately investigated. Of particular interest are the environmental properties associated with these waste materials and their potential impacts if used in recycling applications.

Waste Rock

Depending on the mineral waste processing operations and parent rock involved, acidic leachate from sulfide-based metallic ores, low-level radiation from uranium host rock, or radon gas generation from uranium and phosphate rocks may be environmental concerns. In addition, some waste rock from copper, gold, and uranium mining is leached to recover additional ore. Since cyanide is used for leaching, such waste rock should not be reused without first conducting careful testing. Finally, some iron ore waste rock may contain traces of residual iron, which could cause red staining if exposed for a prolonged period. Such waste rock sources should usually be avoided in applications where aesthetic concerns may be a consideration.

Mill Tailings

Mill tailings from gold mining may typically contain cyanide, whereas tailings from uranium processing may be radioactive and, if so, should not be used in construction applications. Mill tailings from processing of sulfide ores may contain heavy metals such as arsenic. Some sources of taconite tailings have been found to contain asbestos fibers.

Mill tailings consisting of quartz, feldspars, carbonates, oxides, ferro-magnesium minerals, magnetite, and pyrite have been used in the manufacture of calcium silicate bricks, and have also been used as a source of pozzolanic material.

Coal Refuse

Coal refuse usually contains some sulfur-bearing minerals, notably pyrite and marcasite, which could result in an acidic leachate. Pyrites can be removed by sink-float techniques during coal processing. Prior to use in embankment construction, coarse coal refuse banks are usually cleaned to remove any residual coal content for use as fuel, especially if the refuse is in an old bank.

HIGHWAY USES AND PROCESSING REQUIREMENTS

Asphalt Concrete Aggregate, Granular Base, and Embankment or Fill

Waste Rock

Some waste rock has successfully been used as aggregate in construction applications, especially in asphalt paving and in granular base courses. Waste rock has also been used as riprap for banks and channel protection, and as rock fill for embankment construction. Where additional sizing of waste rock is necessary, in order to meet specification requirements, most, if not all, sources can be crushed and/or screened in the same way that a conventional rock source is crushed and screened.

Mill Tailings

Coarse tailings, which are generally considered those tailings that are larger than a 2.0 mm (No. 10) sieve, have been used as aggregate in granular base course, asphalt pavements, chip seals, and, in some cases, concrete structures. Fine tailings have been used as fine aggregate in asphalt paving mixes, particularly overlays, and as an embankment fill material. There are numerous examples of the use of mill tailings in local and state highway construction projects throughout the United States.(7) Conventional crushing and screening techniques can be used for sizing mill tailings.

Coal Refuse

Coal refuse has been used as embankment fill, with some coarse coal refuse also used in stabilized base applications. Most older coal refuse embankments/stockpiles contain a fairly high percentage of carbonaceous material which, because of poor disposal practices in the past, can ignite spontaneously. As mentioned previously, coal refuse banks are cleaned prior to use in order to remove the carbonaceous material. In addition, modern coal refuse disposal practices mitigate this problem by placing the refuse in thin, well-compacted layers and covering all exposed surfaces with several feet of earth fill in order to reduce or eliminate the presence of oxygen needed to initiate or support combustion.

Spent Oil Shale

Spent oil shale has some potential for use as fine aggregate or mineral filler in asphalt paving. Coarse spent oil shale requires crushing and sizing prior to use.

MATERIAL PROPERTIES

The material properties of the various categories of mineral processing wastes are influenced by the characteristics of the parent rock, the mining and processing methods used, and the methods of handling and/or disposing of the mineral by-product. The physical, chemical, and mechanical properties of waste rock, mill tailings, and coarse coal refuse are presented in the following sections.

Physical Properties

Waste Rock

Waste rock results from blasting or ripping and usually consists of a range of sizes, from large blocks down to cobbles and pebbles. Waste rock can be processed to a desired gradation by crushing and sizing, like any other source of aggregate.

The hardness of the waste rock is determined by the rock type. For example, iron ores are often found in hard igneous or metamorphic rock formations, so waste rock from iron or taconite ore processing is usually hard and dense. For the most part, lead and zinc ores are found in limestone and dolomite rock, so the waste rock from processing these ores will have characteristics much like other carbonate aggregates.

The specific gravity or unit weight of most sources of waste rock will be in approximately the same range as the specific gravity or unit weight of conventional aggregates. However, the specific gravity or unit weight of waste rock from the mining of iron ore and taconite will be considerably higher than that of conventional aggregates. The specific gravity of waste rock can be expected to range from 2.4 to 3.0 for most rock types and from 3.2 to 3.6 for waste rock from iron ore and taconite minings.

Mill Tailings

The grain size distribution of mill tailings can vary considerably, depending on the ore processing methods used, the method of handling, and the location of the sample relative to the discharge point in the tailing pond. In general, the lower the concentration or percentage of ore in the parent rock, the greater the amount of processing needed to recover the ore and the finer the particle size of the resultant tailings. Some ores, such as iron ore, are found in relatively high percentages and are fairly easy to separate. Therefore, the resultant tailings are coarser than those from other ores, such as copper, which is found in very low percentages, and requires very fine grinding for separation. Hence, copper tailings are usually quite fine-grained.

Table 9-1 presents a comparison of the particle size distribution of selected samples of copper, gold, iron, lead-zinc, molybdenum, and taconite tailings. These examples represent a cross-section of the varied size distributions of mill tailings. With the exception of some iron ore tailings, it is probable that most mill tailings will be very fine-grained materials with 50 percent or more of the particles passing a 0.075 mm (No. 200) sieve.

Table 9-1. Particle size distribution of selected samples of mill tailings (percent by weight).(8)

Screen Size (Mesh)	Copper Tailings Kennecott, Magna, UT	Gold Tailings Homestake Lead, SD	Iron Ore Tailings Kaiser-Eagle Mtn, CA	Lead-Zinc Tailings ASARCO Mascot, TN	Molybdenum Tailings Climax Climax, CO	Taconite Tailings Hanna Hibbing, MN
19.1 mm	–	–	99.7	–	–	–
12.7 mm	–	–	83.4	–	–	–
9.5 mm	–	–	65.1	–	–	–
6.4 mm	–	–	46.8	–	–	100.0
#10	–	–	17.6	–	100.0	97.0
#20	–	–	7.9	99.6	99.5	92.5
#28	–	–	5.7	N.R.	98.5	N.R.
#35	99.4	–	4.1	91.6	95.8	86.5
#48	98.0	–	2.8	N.R.	89.5	83.0
#65	95.4	100.0	1.9	69.2	81.1	79.0
#100	92.4	97.6	1.4	58.2	70.7	74.0
#150	90.2	94.6	0.9	47.4	60.3	68.0
#200	87.8	90.3	0.7	41.4	50.0	62.5
#270	N.R.	82.4	–	N.R.	44.2	53.0
#325	N.R.	72.1	–	N.R.	41.5	46.0
#400	N.R.	N.R.	–	N.R.	35.5	N.R.

N.R. indicates value not reported.

Other physical properties of mill tailings include specific gravity, unit weight, and moisture content. There is a scarcity of published information on these properties for most types of mill tailings. The specific gravity of mill tailings, based on limited data, appears to range between 2.60 and 3.35, with most tailings having values under 3.0 except for iron ore and taconite tailings. The dry rodded weight of most mill tailings is likely to range from 1450 to 2200 kg/m^3 (90 to 135 lb/ft^3).(13) The moisture content of mill tailings is highly variable, depending on the particle sizing of the tailings and the percent solids of the tailing slurry. Mill tailings are almost always nonplastic.

Table 9-2 provides some published physical property data on a copper tailings sample from Arizona. These data are probably representative of the physical characteristics of most fine-grained tailings materials, especially from the processing of metallic ores.

Table 9-2. Physical properties of copper tailings.(14,15)*

Property	Value
% Passing No. 0.075 mm (No. 200) sieve	31.7
Color	gray
Rainfall Erosion (%)	2.3
Specific Gravity	2.71
AASHTO Classification	A-2-4
Plasticity Index	Nonplastic
* Copper tailings (Duval) from the Sierrita Mine, Duval, Arizona.	

Coal Refuse

Coarse coal refuse is a well-graded material with nearly all particles smaller than 100 mm (4 in). Differences in the range of particle sizes can be attributed to variations in the processing methods used at different coal preparation plants. The predominant portion of coarse coal refuse is from a fine gravel to a coarse to medium sand, with from 0 to 30 percent passing a 0.075 mm (No. 200) sieve.(16) The specific gravity of coarse coal refuse normally ranges from 2.0 to 2.8 for bituminous coal refuse and from 1.8 to 2.5 for anthracite coal refuse. The specific gravity is directly proportional to the plasticity index of the refuse. As the plasticity index increases, the specific gravity also increases. The plasticity index for coarse coal refuse can range from nonplastic up to a value of 16. The natural moisture content of coarse coal refuse has been found to range from 3 percent to as high as 24 percent, but is usually less than 10 percent.(14)

Chemical Properties

There are little to no chemical data on waste rock. Data are presented for mill tailings and coarse coal refuse.

Mill Tailings

Table 9-3 provides chemical composition data for selected samples of copper, gold, iron, lead-zinc, molybdenum, and taconite tailings. As seen from these data, most tailings are siliceous materials. Besides iron ore and taconite tailings, gold and lead-zinc tailings samples also contain fairly substantial percentages of iron. Although pH readings are not reported, some sources of mill tailings, especially those with low calcium and magnesium contents, could be acidic.

Table 9-3. Chemical composition of selected samples of mill tailings (percent by weight).[8]

	Copper Tailings Phelps Dodge Ajo, AZ	Gold Tailings Homestake Lead, SD	Iron Ore Tailings Kaiser Eagle Mtn, CA	Lead-Zinc Tailings USSRM Co. Midvale, UT	Molybdenum Tailings Climax Henderson, CO	Taconite Tailings Eveleth Eveleth, MN
SiO_2	67.3	52.8	48.57	53.91	75 - 80	64.34
Al_2O_3	16.3	1.6	–	2.27	7 - 12	0.25
FeO	2.1	34.0	18.8	11.4	0.2 - 3	11.57
CaO	2.8	1.0	5.74	7.14	0.12 - 1.0	3.57
MgO	N.R.	8.2	4.64	2.16	0.1	4.15
S	0.5	N.R.	0.67	12.0	N.R.	N.R.
Na_2O	N.R.	0.5	N.R.	N.R.	0.4 - 4	N.R.
K_2O	N.R.	N.R.	N.R.	N.R.	4 - 8	N.R.
CO_2	N.R.	N.R.	N.R.	N.R.	N.R.	7.57

N.R. indicates value not reported.

Coal Refuse

Table 9-4 provides composite chemical composition data for a total of 14 different samples of coarse coal refuse that were analyzed as part of an investigation of the possible use of coal refuse-fly ash blends as base course material.[14] There is no typical chemical composition for coarse coal refuse and the sulfur content of the refuse is related to that of the coal from which it was derived. Like mill tailings, coarse coal refuse is a siliceous material, but it has considerably more alumina than tailings. Coarse coal refuse is almost always acidic.

Table 9-4. Range of chemical composition of coarse coal refuse samples (percent by weight).[14]

Constituent	Composition Range
SiO_2	37 - 62
Al_2O_3	16.4 - 32.4
Fe_2O_3	43 - 29.1
CaO	0.1 - 4.6
MgO	0.6 - 1.6
S	0.5 - 7.1
Na_2O	0.2 - 1.3
K_2O	2.1 - 4.7

Because of its low pH and presence of pyritic sulfur, there are several concerns related to the chemical composition of coarse coal refuse, including the following:

Corrosivity: The pH value of the refuse in water should be determined for proper selection of type of underdrain or other drain pipes. Extremely acidic refuse in the subgrade will require the use of special compositions of coatings on pipes to avoid deterioration or corrosion of the pipe.

Deleterious Substances: The oxidation of the pyrite and marcasite in coal refuse is deleterious and produces an acid discharge upon contact with water. Bituminous coal refuse composed of poorly consolidated siltstone can have high tendency toward weathering and can disintegrate under environmental conditions.

Sulfate Content: Chemical parameters of coal refuse should be considered when using it for embankment or granular base applications. The determination of the sulfate levels leached from the refuse materials is required to design for the protection of concrete structures. The following tests have been used to determine the sulfate levels: British Standard 1377, Methods of Test for Soils for Civil Engineering Purpose; Test 9 - Determination of the total sulfate content of soil; and Test 10 - Determination of the sulfate content of ground water and of aqueous soil extracts.(17) Typically, the sulfate content of the refuse is in the range of 0.01 to 4.7 percent.

Mechanical Properties

The mechanical properties of most interest with respect to waste rock, mill tailings and coarse coal refuse are shear strength, moisture-density characteristics, and permeability. A limited amount of data on these properties are available for waste rock, but the properties would be expected to be similar to those of conventional mineral aggregates of similar rock type and composition.

Mill Tailings

Mill tailings are virtually cohesionless materials with internal friction angles that can range from 28 to 45 degrees. Maximum dry density values may range from 1600 to 2300 kg/m^3 (100 to 140 lb/ft^3), with optimum moisture content values that may be between 10 to 18 percent. Permeability values ranging from 10^{-2} to 10^{-4} cm/sec have been reported, with most values in the 10^{-3} cm/sec range.(13)

Coal Refuse

The shear strength of coarse coal refuse is derived primarily from internal friction with comparatively low cohesion. Friction angles have been found to range from 25 to 42 degrees, with anthracite refuse normally having lower friction angles than bituminous refuse. The optimum moisture content may range from 6 to 15 percent, while the maximum dry density can range from 1300 kg/m^3 (80 lb/ft^3) to 2000 kg/m^3 (120 lb/ft^3). A wide variety of moisture-density curves have been developed for coarse coal refuse because of the variability of the material, although most moisture-density curves are relatively flat. Permeability values of compacted coarse coal refuse can vary over a fairly wide range from 10^{-4} to 10^{-7} cm/sec,(14) depending on the gradation of the refuse before and after compaction.

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INTRODUCTION

Both waste rock and mill tailings have physical properties that are suitable, in most cases, for use in asphalt paving applications. Coarse coal refuse is generally unsuitable for such use.

Waste Rock

Waste rocks derived from most ore processing sources can be considered for use in asphalt paving applications provided they satisfy conventional asphalt paving aggregate requirements. Waste rock should not contain deleterious components and must not be commingled with unsuitable materials. Waste rock from iron ore processing is usually either trap rock or granite, which makes an excellent source of aggregate.

Mill Tailings

Mill tailings have successfully been used as aggregate in asphalt paving applications. Generally, the coarser, sand-size fractions of mill tailings can also be considered for use as coarse aggregates provided there are no harmful or reactive chemical components concentrated from the host rock and the tailings can satisfy the conventional paving aggregate requirements. Despite the fine size of most mill tailings, these materials can be blended with coarser materials, such as gravel, to bring the overall fines content to an acceptable range. It is also possible to separate the coarser fraction of tailings by classifying prior to disposal. Depending on the source of the mill tailings, there may be some concern with trace metals remaining after ore processing that could potentially leach from fine-grained tailings, which have a high surface area.

PERFORMANCE RECORD

Over the years, there have been numerous examples of the use of mineral processing wastes, notably waste rock and mill tailings, in asphalt paving applications. The current use of mineral processing wastes as aggregate in hot mix asphalt is not a common practice, due in great part to the relatively remote location of many sources of these wastes. Although examples of mineral processing waste utilization are not well documented, it is known that waste rock has been used as coarse aggregate in asphalt paving in at least 8 states and that mill tailings have been used in asphalt paving in at least 13 states.(1) There are also two states (Kentucky and Pennsylvania) where coal refuse has been used to a limited extent in asphalt paving. Table 9-5 is a summary of the known U.S. mining and mineral processing wastes in asphalt paving in at least 19 different states. A few state agencies have been involved in recent research or field trials, but only five states (Kansas, Missouri, Nevada, New York, and Oklahoma) report any ongoing or upcoming research on the use of mineral processing wastes as aggregate or mineral filler in hot mix asphalt.(2)

Table 9-5. Summary of the use of mining and mineral processing wastes in asphalt paving mixtures in the United States.

State	Type of Mining Waste Used	Project Location(s)	Estimated Tonnage
California	Gold Dredge Tailings Iron Ore Tailings	Sacramento Freeways County Road near Eagle Mountain	Not known Not known
Illinois	Lead-Zinc Tailings	Local Roads in Northwest Illinois	90,000 tonnes (100,000 tons)
Kansas	Lead-Zinc Tailings (Chert)	Southeast corner of Kansas	Not known
Kentucky	Bituminous Coal Refuse	Low volume roads	Not known
Louisiana	Iron Ore Waste Rock	Location not known	Not known
Minnesota	Coarse Taconite Tailings	Roads and bridge decks in Duluth and Minneapolis-St. Paul areas	Not known, but substantial amounts
Missouri	Barite Tailings (Tiff Chert) Lead-Zinc Tailings (Chert) Iron Waste Rock (Trap Rock) Lead Waste Rock	Local roads in east central Missouri Southwest corner of Missouri Southeast part of Missouri Street paving in St. Louis area	Not known Substantial amounts Not known Not known
Nevada	Barite Tailings (Chert)	I-80 Resurfacing near Battle Mountain	Not known
New Jersey	Iron Ore Tailings	Northwest part of New Jersey	Not known
New Mexico	Molybdenum Tailings and Waste Rock	North central part of New Mexico	Not known
New York	Iron Ore Waste Rock	Essex and St. Lawrence Counties	Not known -- asphalt use since 1930
Oklahoma	Lead-Zinc Tailings (Chert)	Northeast corner of Oklahoma	Substantial amounts
Pennsylvania	Anthracite Coal Refuse Burnt Anthracite Refuse (Red Dog) Iron Ore Waste Rock	4 experimental test sections -- Luzerne Co. Penn. Turnpike N.E. Extension - Luzerne Co. PA Turnpike - Berks & Chester Cos.	Limited amounts Not known Substantial amounts
South Dakota	Gold Waste Rock	Seal Coat Rt. 35 near Lead	Not known

Table 9-5. Summary of the use of mining and mineral processing wastes in asphalt paving mixtures in the United States (continued).

State	Type of Mining Waste Used	Project Location(s)	Estimated Tonnage
Tennessee	Zinc Coarse Tailings	Eastern part of Tennessee	Not known
Utah	Classified Copper Mill Tailings	Mineral Filler in Salt Lake City area	Limited amounts
Washington	Lead-Zinc Waste Rock	Northeast corner of Washington	Not known
Wisconsin	Coarse Iron Ore Tailings and Waste Rock Lead-Zinc Tailings	U.S. Rt. 141 north of Milwaukee Local roads in southwest Wisconsin	Not known Not known
Wyoming	Coarse Iron Ore Tailings	Southeastern part of Wyoming	Limited amounts

Waste Rock

Colorado and South Dakota have used crushed rock waste from gold mining operations in road construction, including asphalt paving. Lead waste rock has been used in bituminous mixtures in Missouri. Lead-zinc waste rock has been used for resurfacing by local and county agencies in Washington. Trap rock from iron ore processing has been crushed to meet standard specification requirements for hot mix aggregate in New Jersey and Pennsylvania.

In Missouri and Illinois, iron waste rock has been used as a skid-resistant aggregate for asphalt paving. In New Mexico, waste rock from molybdenum mining operations has been used as aggregate in asphalt paving with satisfactory performance.(3) Most waste rock is generated in the western United States, particularly in copper mining areas such as Arizona and Utah.

Mill Tailings

In Minnesota, taconite tailings improved the frictional resistance of asphalt overlays, and, on this basis, this material is still used in the northern part of the state for hot mix resurfacing. In New Mexico, the coarse tailings from molybdenum mining operations have been used as aggregate in asphalt paving with satisfactory performance.(3) At least 12 states, including Alabama, California, Illinois, Kansas, Minnesota, Missouri, Nevada, New Jersey, New Mexico, New York, Oklahoma, and Wisconsin, have used or continue to use mill tailings for asphalt paving applications. Utah reportedly has used the fines from copper mining operations as a mineral filler in asphalt.(2)

MATERIAL PROCESSING REQUIREMENTS

Waste Rock

Crushing and Screening

Many sources of waste rock are geologically similar to natural sources of construction aggregate, and, therefore, can be crushed and/or screened using conventional aggregate processing equipment. Waste rock from iron ore or taconite processing may be heavier than conventional aggregate.

Mill Tailings

Dewatering

Mill tailings may have to be dried to reduce the moisture content, or may require selective screening and dewatering prior to being introduced into a hot mix asphalt plant. When reclaimed from a tailings pond, stockpiling and air drying for a period of time may be sufficient to reduce the moisture content of some tailings by evaporation, especially in arid areas.

Crushing and Screening

Screening and/or crushing may be required in some cases to produce a suitable aggregate like product from mill tailings or to meet gradation specifications. Crushing is not normally required, with the possible exception of some coarse tailings that may require size reduction of oversize particles. Some fine-sized tailings, such as copper mill tailings, can be classified prior to disposal in order to separate the coarser fraction of the tailings for subsequent reuse.

ENGINEERING PROPERTIES

Waste Rock

Some of the properties of waste rock that are of interest when used in asphalt paving applications include gradation, shape and texture, specific gravity, shear strength, and abrasion resistance.

Gradation: Waste rock is often homogeneous but can vary widely in size from boulders down to gravel, due to variations in ore formation and different mining techniques. In general, most sources of waste rock can be reduced to a desired gradation by normal crushing and sizing methods.

Shape and Texture: Waste rock is coarse, hard, and angular in shape and can vary in size from large boulders or blocks down to gravel.

Specific Gravity: The average specific gravity of waste rock is about 2.65, with a range from 2.4 to 3.6 depending on the nature of the mineral constituents. Specific gravity may be used to determine other important properties such as void ratio, porosity, and degree of saturation.(4)

Shear Strength: Typical values for the angle of internal friction for waste rock materials often exceed 35 degrees and contribute to high bearing capacity and stability.

Abrasion Resistance: Most sources of waste rock are able to satisfy abrasion loss requirements. Waste rocks from the processing of iron ore or taconite are usually quite dense and often have relatively low abrasion loss values.

Mill Tailings

Some of the properties of mill tailings that are of interest when mill tailings are used in asphalt paving applications include gradation, shape and texture, specific gravity, absorption, unit weight, and stripping resistance.

Gradation: Mill tailings are usually very fine-graded, cohesionless materials. They consist of hard, angular siliceous particles with a high percentage of fines. Typically, mill tailings range from sand to silt-clay particle size with 40 to 90 percent passing a 0.075 μm (No. 200) sieve. They are disposed of in slurry form by pumping into large ponds.(5)

Shape and Texture: Mill tailings are uniform in particle shape and texture. Mill tailings typically consist of hard, angular, siliceous particles with a high percentage of fines.

Specific Gravity: The specific gravity of tailings ranges from about 2.0 to 3.5, depending on the mineralogical composition.

Absorption: Water absorption values for lead, zinc, copper and iron ore tailings are typically higher than the standard maximum limit of 1.0 percent for fine aggregate in asphalt paving mixes.(6,7)

Unit Weight: Iron ore tailings and taconite tailings from northern Minnesota have high unit weight values, up to as high as 2750 kg/m^3 (170 lb/ft^3). The dry rodded weight of most other tailings sources is expected to range from 1450 kg/m^3 (90 lb/ft^3) to 2200 kg/m^3 (135 lb/ft^3), which is comparable to that of most natural aggregates, which are approximately 2000 kg/m^3 (125 lb/ft^3) to 2300 kg/m^3 (140 lb/ft^3).(5)

Stripping Resistance: Iron ore and taconite tailings do not appear to be susceptible to stripping. Mill tailings from other sources should be evaluated for stripping potential as part of the normal asphalt paving mix design procedures.

DESIGN CONSIDERATIONS

Mix Design

Waste Rock

Waste rock for use in hot mix asphalt must comply with the requirements for coarse aggregate in bituminous mixtures.(8) Asphalt mixes containing waste rock can be designed using standard laboratory procedures.

The potential for stripping of asphalt mixes containing waste rock should be assessed in the laboratory as part of the overall hot mix asphalt mix design. Stripping resistance can be enhanced by adding hydrated lime or a proprietary antistripping additive.

Mill Tailings

There are no standard specifications for the use of mill tailings in hot mix asphalt paving. There are, however, a few states that have historically used different types of mill tailings as a fine aggregate, a mineral filler, or in some cases, as a coarse aggregate in asphalt paving mixes. Tailings should meet the appropriate specification requirements for their intended use, either as a source of fine aggregate(9) or mineral filler.(10) Asphalt mixes containing mill tailings can be designed using standard laboratory procedures. The potential for stripping of asphalt mixes containing mill tailings should also be assessed in the laboratory as part of the overall design.

Structural Design

Waste Rock

Conventional AASHTO pavement structural design methods(11) are appropriate for the thickness design of asphalt paving mixtures incorporating waste rock as the coarse aggregate.

Mill Tailings

Conventional AASHTO pavement structural design methods(11) are also appropriate for the thickness design of asphalt paving mixtures incorporating mill tailings as the fine aggregate, mineral filler, or coarse aggregate.

CONSTRUCTION PROCEDURES

Material Handling and Storage

The same methods and equipment used to store or stockpile conventional aggregates are applicable for waste rock and mill tailings. However, users of those materials should be aware that such materials usually have an acid potential and that leaching may occur during stockpiling or heating in the asphalt plants.

Placing and Compacting

The same methods and equipment used for conventional pavements are applicable to asphalt pavements containing waste rock or mill tailings. Compaction operations should be visually inspected on a continuous basis to ensure that the specified degree of compaction can be achieved and there is no movement under the action of compaction equipment.

Quality Control

The same field testing procedures used for conventional hot mix asphalt mixes should be used for mixes containing mineral processing wastes. Mixes should be sampled in accordance with AASHTO T168,(12) and tested for specific gravity in accordance with ASTM D2726,(13) and in-place density in accordance with ASTM D2950.(14)

UNRESOLVED ISSUES

There is a need to establish general environmental criteria for the selection of mining or mineral processing by-products to be used in paving applications. More knowledge is needed concerning the variation in mineral processing operations that can alter the quality of such by-products.

More specifically, there is a need to investigate and analyze the environmental impact of some waste rock and mill tailings sources that may contain inorganic metal and sulfide-based metallic ore constituents to assess the level of leachability, if any, when used in hot mix asphalt. Mill tailings may contain concentrations of certain inorganic metal constituents that may be leachable. Some waste rock and tailings have been leached with cyanide as a means of further ore extraction. Certain sources of taconite are known to contain asbestiform fibers. Uranium mill tailings can be a source of residual radiation, and phosphate rock can be a source of low-level radiation resulting from radon gas.

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INTRODUCTION

Waste rock, mill tailings, and coarse coal refuse can be used as a granular base in pavement construction applications. Burnt coal refuse (or red dog) from banks or piles that have caught on fire has also been used as a granular base material.

Waste Rock

Waste rock derived from igneous or metamorphic rocks, as well as properly consolidated limestones, sandstones, and dolomites are generally suitable for granular base and subbase applications, provided the waste rocks do not contain deleterious components and are not commingled with overburden.

Mill Tailings

Coarser-sized mill tailings can be used in granular base and subbase applications. Generally, the coarser, sand-size fractions of mill tailings can also be considered for use as construction aggregates, provided there are no harmful or reactive chemical components concentrated from the host rock. Despite the fine size of most mill tailings, these materials can be blended with coarser materials, such as gravel, to bring the overall fines content to an acceptable range, or can often be classified prior to initial disposal in order to recover the coarser fraction for possible use.

Coal Refuse

Coarse coal refuse can be used as aggregate in granular base applications. Burnt coal refuse (red dog) is also a suitable granular base material. Proper compaction of coarse coal refuse to its maximum dry density is necessary to achieve stability within a pavement structure. Fine coal refuse slurry has little or no load carrying capability and is, therefore, unsuitable for use as a construction material.

The carbonaceous content of coal refuse, its potential for spontaneous combustion, as well as its pyritic or sulfur composition and acidic nature are causes for environmental concern.

PERFORMANCE RECORD

The use of mineral processing waste as a granular base material is not very common, since many mineral processing wastes are not close to urban areas where construction materials are needed. There is little current research or actual reported use of such wastes in granular base construction.

Waste Rock

A review of the published and unpublished reports reveals that at least 13 states have made use of some source of waste rock in their state highway construction programs, sometimes dating back as many as 50 years. However, it does not appear that any state highway agencies or universities have been involved in research for waste rock use as aggregate in granular base or subbase applications.(1)

Mill Tailings

At least five states, including Alabama, Alaska, Arizona, Arkansas, and Virginia, have reported using mill tailings as aggregate in granular base course applications, although the Arkansas experience was not considered successful, due to poor performance or economics.(1) Other states that have made some use of mill tailings for granular base or subbase construction in the past include California, Colorado, Idaho, Illinois, Michigan, Minnesota, and Tennessee.(2)

Coal Refuse

Coal refuse has been successfully used in cement stabilized base applications in Europe. The success of this material for use in this application is reportedly dependent on proper compaction. There has been occasional use of coal refuse in Alabama, Kentucky, Virginia, and West Virginia as an alternative material for bases and subbases.(1,2,3)

The Pennsylvania Department of Transportation has rejected anthracite refuse usage as aggregate for base and subbase courses because of high percent losses in the sodium sulfate (soundness test).(4,5) West Virginia is evaluating the use of coal refuse as subbase material.

The Ministry of Transport in the United Kingdom permits the use of incinerated coal refuse (well- burnt, nonplastic shale) as a granular subbase material in Ministry controlled road work.(6)

MATERIAL PROCESSING REQUIREMENTS

Waste Rock

Crushing and Screening

Where the waste rock consists of hard, stable chunks of rock with no overburden or vegetation, granular aggregate material can be produced by crushing. Crushing and screening can be accomplished using conventional aggregate processing equipment.

Mill Tailings

Dewatering

Processing of certain tailings sources (such as dewatering, reclaiming, and selective size classification) may be necessary, although this is not common practice and can be costly. Tailings reclaimed from ponds will normally require a reasonable period of time to dewater, depending on climatic conditions.

Screening

Some tailings materials may contain sufficient coarse sizes (greater than 2.0 mm (No. 10 sieve) or 4.75 mm (No.4 sieve)) that could be classified and separated from the finer fraction for possible use as a granular base material.

Coal Refuse

Separation or Cleaning

The basic coal refuse processing techniques used in coal preparation plants are separation of the coal from the unwanted foreign matter (pyrite and marcasite). The equipment most frequently used in these plants to classify the refuse is based on the difference in specific gravity between the coal and the host rock.

For older refuse banks, additional separation or cleaning may be required in the field to remove and recover the combustible portion of coarse coal refuse for use as fuel, prior to using the remaining refuse material as a granular base or subbase material. Such cleaning also serves to prevent potential spontaneous combustion of the refuse.

ENGINEERING PROPERTIES

Waste Rock

Some of the properties of waste rock that are of particular interest when waste rock is used in granular base applications include gradation, specific gravity, and shear strength.

Gradation: Waste rock is generally coarse, crushed, or blocky material covering a range of sizes, from very large boulders and rocks to sand-size particles and dust. Waste rock can be crushed and screened for use or blended with other aggregates to generate a product suitable for granular base or subbase aggregate.

Specific Gravity: The average specific gravity of waste rock is about 2.65, with a range from 2.4 to 3.6 depending on the nature of the mineral constituents. Specific gravity may be used to determine other important properties such as void ratio or porosity.(7)

Shear Strength: Typical values of the angle of internal friction of most waste rock sources exceed 35 degrees and contribute to relatively high bearing capacity and stability.

Mill Tailings

Some of the properties of mill tailings that are of particular interest when mill tailings are used in granular base applications include gradation, particle shape and texture, unit weight, and moisture-density characteristics. It is difficult to definitively characterize representative samples of mill tailings materials because of the number of sources and the variations in the degree of processing that can be encountered.

Gradation: Typically, mill tailings range from sand to silt-clay in particle size with 40 to 90 percent passing a 0.075 mm (No. 200) sieve. They are normally disposed of in slurry form by pumping into large retention areas/settlement ponds.(8) Despite the fine size of most mill tailings, these materials can be classified prior to disposal or blended with coarser materials, such as gravel, to bring the overall fines content to an acceptable range for use as a construction aggregate.

Shape and Texture: Mill tailings consist of hard, angular, siliceous particles.

Unit Weight: Iron and taconite tailings typically have high unit weight values up to as high as 2700 kg/m^3 (170 lb/ft^3). The unit weight of most other tailings sources is expected to range from 1500 kg/m^3 (90 lb/ft^3) to 2200 kg/m^3 (135 lb/ft^3), which is comparable to that of most natural aggregates, which are approximately 2,000 kg/m^3 (125 lb/ft^3) to 2300 kg/m^3 (140 lb/ft^3).(8)

Moisture-Density Characteristics: With the possible exception of iron ore or taconite tailings, most mill tailings have an optimum moisture content in the range of 10 to 18 percent. The maximum dry density of most tailings sources is in the range of 1600 kg/m^3 (100 lb/ft^3) to 2025 kg/m^3 (125 lb/ft^3).(9)

Coal Refuse

Some of the properties of coal refuse that are of particular interest when coal refuse is used in granular base applications include gradation, particle shape/ texture, moisture-density characteristics, shear strength, permeability, and frost susceptibility.

Gradation: Coarse refuse, which can contain particles that are greater than a 4.75 mm (No. 4) sieve, is generally a well-graded material for particles up to 100 mm (4 in) in size. These particles consist mainly of slate or shale with some sandstone or clay. Most coarse refuse contains particles that may break down under compaction equipment, resulting in a finer gradation following placement.

Shape/Texture: Coal refuse is composed mainly of flat slate or shale particles with some coal, sandstone, and clay intermixed. Such particles may weather or break down easily.

Moisture-Density Characteristics: Based on available data, the optimum moisture content of coarse coal refuse is likely to range from 6 to 15 percent and its maximum dry density may vary from 1300 kg/m^3 (80 lb/ft^3) to 2000 kg/m^3 (120 lb/ft^3).(6)

Shear Strength: The shear strength of coarse coal refuse can be highly variable. The angle of internal friction values for coarse coal refuse have been reported to be between 18 and 42 degrees.(10) The shear strength of coal refuse is usually lower than that obtained for granular materials with similar properties, but can be increased by proper compaction.(6,10,11) Previous experience with coal refuse usage as a construction material has demonstrated that the shear strength of the refuse is acceptable if proper compaction measures are achieved during construction.(10,12)

Permeability: The permeability of coarse coal refuse can be highly variable and should be determined for each particular source and application. It is related to the composition of the refuse, its degradation during compaction, and the degree of compaction.(10,13) The permeability of coarse coal refuse is lower than that of other granular materials with a similar grain size distribution. Conventional formulas relating permeability to particle size distribution and uniformity are not applicable for estimating the permeability of coarse coal refuse.(14)

Low permeability values are desirable in order to reduce air circulation and to reduce the potential for spontaneous combustion, oxidation of pyrites, and acidic leachate. Fly ash may be added to the refuse for this purpose. The average permeability for coal refuse-fly ash mixtures is significantly lower (10^{-6} to 10^{-7} cm/sec) than that for the coal refuse alone (10^{-3} x 10^{-5} cm/sec) because fly ash fills the voids of the coal refuse.(14,15)

Frost Susceptibility: Coal refuse is susceptible to frost heave, especially burnt coal refuse. Frost damage can reportedly be reduced or eliminated by the addition of cement to the refuse.(16)

DESIGN CONSIDERATIONS

Waste Rock

There are no standard specifications for the use of crushed waste rock in granular base applications. Most sources of waste rock are of a quality that is comparable to conventional aggregates used as granular base materials, so specifications applicable to such aggregates can probably be used, provided sufficient compaction is achieved.

Mill Tailings

There are no standard specifications for mill tailings as an aggregate in granular base. The tailings must meet sizing requirements and satisfy standard Proctor moisture-density criteria.(17) Durability testing may also be required. Most tailings sources may have an excess amount of material finer than the 4.75 mm (No. 4) or 2.00 mm (No. 10) sieve. This will either limit their use in granular base course applications or necessitate separation and use of the coarser fraction of the tailings.

Mill tailings to be used in granular base should also be tested in accordance with AASHTO test methods T234(18) and T236(19) to determine the shear strength characteristics and to define the angle of internal friction and cohesion of the material tested. The California Bearing Ratio (CBR) test (AASHTO T193)(20) can also be used to evaluate the subgrade bearing capacity.(22)

Coal Refuse

Tests for combustion potential and standard Proctor moisture-density criteria should be carried out for all coal refuse that is considered for use in granular base construction. Leaching and swelling indexes, porosity, freeze-thaw tests, and wet-dry swelling tests are also recommended. Water soluble sulfate testing methods and specifications for determining the amount of sulfate found in coal refuse and measures used to overcome such sulfate content are available from the British National Coal Board.(21) The introduction of fly ash to coal refuse may help to neutralize the acidity of the refuse, increase its moisture-holding capacity, increase its pore space volume, and reduce its erodability.(22) Lime and/or cement added as a binding agent with the fly ash produces a pozzolanic reaction, which can provide added strength and durability to the coal refuse/fly ash mixture.(2)

Coal refuse to be used in granular base should also be tested in accordance with AASHTO test methods T234(23) and T236(24) to determine the shear strength characteristics and to define the angle of internal friction and cohesion of the material tested. The CBR test (AASHTO T193)(25) can also be used to evaluate the subgrade bearing capacity.(22)

CONSTRUCTION PROCEDURES

Material Handling and Storage

Waste Rock and Mill Tailings

The same methods and equipment used to store or stockpile conventional aggregates are applicable for waste rock or mill tailings.

Coal Refuse

Prior to using the refuse to construct a granular base, the bank should be cleaned or processed to recover the residual coal or combustible matter. This ordinarily involves a screening of the refuse, which also removes oversize and deleterious materials.

Placing and Compacting

Waste Rock

The same methods and equipment used to place and compact conventional aggregate can be used for the placement of waste rock. As with any other oversize rock placement, compaction operations must be inspected on a continuous basis to ensure that the specified degree of compaction can be achieved, or that there is no movement under the action of compaction equipment.

Mill Tailings

No modifications to normal construction equipment or procedures are needed, except that tailings may need to be dried to near optimum moisture content prior to placement and compaction.

Coal Refuse

No significant modifications to normal construction procedures are needed, except that possible material breakdown under compaction equipment requires more repetitive testing in the field. Proper compaction of coal refuse reduces air voids to less than 10 percent, and can reduce the permeability to less than 10^{-5} to 10^{-6} cm/sec, which is very low. Under such conditions, the material is sufficiently dense for base course construction and the potential for ignition is substantially reduced.(6)

Quality Control

Waste Rock and Mill Tailings

The same test procedures used for conventional aggregate are appropriate for waste rock and mill tailings, although waste rock may have particles that are too large for certain in-place density tests. The same field test procedure used for conventional aggregate are recommended for granular base applications when using waste rock or mill tailings. Standard laboratory and field test methods for compacted density are given by AASHTO T191,(26) T205,(27) T238,(28) and T239.(29)

Coal Refuse

Strict compaction control testing must also be performed when using coal refuse as a base. A determination of the sulfate levels leached from the coarse refuse materials is required in order to design for the protection of any adjacent concrete structures. The pH value of the refuse in water should also be determined for proper selection of type of underdrain or other drain pipes.

UNRESOLVED ISSUES

Relatively little is known about how variations in mineral processing operations can alter the quality of mineral processing wastes.(30)

Waste Rock and Mill Tailings

There is also a need to determine whether specific sources of such materials are environmentally suitable for use in granular base construction. In addition, there is a need to develop engineering data on the design properties and performance of potential waste rock and/or mill tailings used in granular base applications.

Coal Refuse

There is a need to further evaluate the environmental concerns regarding the potential for acidic leachate from coarse coal refuse used in granular base applications. The production of such leachate is caused by the oxidation of pyrite and marcasite with the presence of high sulfur content. If acidic leachate were to be produced over time, it could contaminate groundwater, adversely impact the ecosystem, and cause deterioration or corrosion of underdrains or other drain pipes.

More information may be needed to completely mitigate concerns associated with the spontaneous combustion potential of coarse coal refuse.

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INTRODUCTION

Several different types of mineral processing wastes, particularly mill tailings and coarse coal refuse, have been successfully used to construct highway embankments. To a lesser extent, waste rock has also been sporadically used as a fill material in highway construction.

Waste Rock

Waste rock derived from igneous or metamorphic rocks, as well as properly consolidated limestones, sandstones and dolomites, are generally suitable for use in embankment or fill construction applications, provided the rocks do not contain deleterious components and are not commingled with overburden. Prior to use, some consideration should be given to the leaching potential of waste rock from sulfide-based ore bodies (such as lead, zinc, or silver) or waste rock subjected to heap leaching.

Mill Tailings

Mill tailings have been used previously in embankment and fill applications by some state and local highway agencies. Generally, the coarser, sand-size fractions of mill tailings can also be used as a construction aggregate, provided there are no harmful or reactive chemical components concentrated from the host rock. Despite the fine size of most mill tailings, these materials can be blended with coarser materials, such as gravel, to bring the overall fines content to an acceptable range, or can often be classified prior to initial disposal in order to recover the coarser fraction for possible use. However, the metal leaching potential of these materials can be a cause for environmental concern and should be thoroughly investigated prior to embankment use.

Coal Refuse

Coarse coal refuse can be used in embankment applications. Proper compaction of coarse coal refuse to its maximum dry density is necessary to achieve stability and to minimize the potential for spontaneous combustion. Burnt coal refuse (red dog) is also a suitable embankment or fill material. Fine coal refuse slurry has little or no load carrying capability and is, therefore, unsuitable for use as a construction material.

Potential problems with spontaneous combustion associated with the carbonaceous content of coal refuse, its pyritic or sulfur composition, and acidic nature are causes for environmental concern.

PERFORMANCE RECORD

Mineral processing wastes have been used in a number of states during the past 30 to 40 years for embankment applications where such materials have been available, acceptable, and economical.

Although uses of mining and mineral processing wastes for highway embankment construction have not generally been well documented over the years, it is known that these materials have been used for such purposes in at least 14 different states. There are also at least two other examples (feldspar tailings in North Carolina and coal refuse in Ohio) where these materials have been used on a local basis as fill and approved for highway construction. Table 9-6 is a summary of the known uses of mining and mineral processing wastes in embankments in these 16 different states.(1)

Table 9-6. List of mining waste embankment or structural backfill projects constructed in the United States.

State	Type of Mining Waste Used	Project Location(s)	Estimated Tonnage or Volume
Alaska	Mill tailings	Location not known	Not known
California	Gold dredge tailings	Sacramento area	Substantial amounts
Colorado	Gold mill tailings Coal mine wastes	North central part of California Location not known	Not known Not known
Idaho	Lead-zinc tailings Gold dredge tailings	I-90 near Kellogg Forest Road in Custer Co.	>765,000 m^3 (>1 million yd^3) Not known
Illinois	Coal refuse	I-57 in Franklin Co.	Not known
Indiana	Coal overburden	Two interstate highways	Not known
Michigan	Copper waste rock Copper stamp sands Iron waste rock	US Rte 45 in Military Hills U.S. Rte 41 near Houghton U.S. Rte 2 near Ironwood	350,000 m^3 (460,000 yd^3) 46,000 m^3 (60,000 yd^3) 130,000 m^3 (250,000 yd^3)
Minnesota	Taconite tailings	Northeast part of Minnesota	Not known
Missouri	Iron waste rock	Southeast part of Missouri	Not known

Table 9-6. List of mining waste embankment or structural backfill projects constructed in the United States (continued).

State	Type of Mining Waste Used	Project Location(s)	Estimated Tonnage or Volume
New York	Iron waste rock	Northwest part of New York	Not known
North Carolina	Feldspar tailings	Western part of North Carolina	Probably small amounts
Ohio	Bituminous coal refuse	Southeast part of Ohio	Probably small amounts
Pennsylvania	Anthracite coal refuse Anthracite coal refuse Bituminous coal refuse	Cross Valley Expressway near Wilkes Barre I-81 near Hazleton US Rte 219 relocation near Ebensburg	115 million m^3 (1.5 million yd^3) Substantial amounts 145,000 m^3 (190,000 yd^3)
South Dakota	Gold mill tailings	Western part of South Dakota	Not known
Utah	Copper mill tailings Copper mill tailings	I-215 west of Salt Lake City Other roadways near Salt Lake City	3 million (3.3 million tons) 2 million (2.2 million tons)
Washington	Lead-zinc waste rock	County roads in Metaline Falls area, northeast corner of Washington	Not known

Waste Rock

Waste rock derived from all sources may be used for embankment applications provided it satisfies applicable specification requirements for rock base. Waste rock should not contain deleterious components and must not be commingled with unsuitable materials. Currently, New York is the only state that is reportedly using waste rock as highway material. It is being used as stone fill for embankments and as rip rap for bank and channel protection. Performance has been acceptable in each application.(2) Other states that have made some use of waste rock for embankment construction in the past include Arizona, Colorado, Michigan, and Washington.(1)

Mill Tailings

The coarser, sand-size fractions of most mill tailings ordinarily make acceptable embankment construction materials, provided there are no harmful or reactive chemical components contained in the tailings. Despite the fine size of most of tailing materials, they can be readily classified or blended with coarser materials, such as natural gravel, to bring the overall fines content to a more acceptable range.

In the last 15 to 25 years, some very large highway embankments have been constructed using mill tailings. Copper tailings have been used in Utah and Michigan, lead-zinc tailings in Idaho, feldspar tailings in North Carolina, and gold tailings in California and Colorado. Although some embankment applications may not have been well documented, their performance has been generally described as good to very good for this type of application.(1)

In 1994, it was reported that at least 11 local or state agencies in Alaska, California, Colorado, Idaho, Michigan, Minnesota, Missouri, North Carolina, South Dakota, Utah, and Washington have been involved, at one time or another, in mill tailings use in embankment applications.(2)

Coal Refuse

Pennsylvania has had successful experiences with the use of coarse coal mine refuse in at least four embankment construction projects. Both anthracite and bituminous coal refuse have been used.(3) Other states with some experience in coal refuse embankment construction include Illinois, Indiana, Maryland, and Ohio.(2) Also, some local usage of coarse coal refuse as a fill material has been previously indicated in Colorado and Kentucky.(1) The Federal Highway Administration has prepared a manual recommending the appropriate methods for using coal refuse to build highway embankments.(4)

Great Britain has been a forerunner in the utilization of coal mine refuse in highway construction. The Ministry of Transport in Great Britain permits the use of coal refuse (well-burnt nonplastic shale) as an alternative material source for the construction of embankments.(5)

MATERIAL PROCESSING REQUIREMENTS

Waste Rock

Crushing

Crushing and sizing is the only processing required to make use of oversize waste rock in embankments. Waste rock should be free of overburden and vegetation before crushing.

Mill Tailings

Dewatering

For certain mill tailings sources, some processing (such as dewatering, reclaiming, and selective size classification) may be necessary, although this is not common practice and can be costly. Tailings reclaimed from ponds will normally require a reasonable period of time to dewater, depending on climatic conditions.

Screening

Some fine tailings can be size classified to recover a coarser fraction (between the 4.75 mm (No. 4) and 0.075 mm (No. 200) sieves) for use as an embankment construction material.

Coal Refuse

Separation or Cleaning

Various mineral processing techniques are used to separate the coal from the unwanted foreign matter in coal preparation plants. The equipment most frequently used in these plants to classify the refuse is based on the difference in specific gravity between the coal and the host rock.

Additional separation or cleaning may be required in the field in order to remove and recover the combustible portion of coarse coal refuse for use as fuel, prior to placing the remaining refuse material in an embankment. This is particularly the case for older refuse banks.

ENGINEERING PROPERTIES

Waste Rock

Some of the properties of waste rock that are of particular interest when waste rock is used in embankment or fill applications include gradation, specific gravity, and shear strength.

Gradation: Waste rock is generally coarse, crushed, or blocky material covering a range of sizes, from very large boulders to fine sand-size particles and dust. Waste rock can be processed and blended with other aggregates to generate a product suitable for use in embankment construction.

Specific Gravity: The average specific gravity of waste rock is about 2.65, with a range from 2.4 to 3.6 depending on the nature of the mineral constituents. Specific gravity may be used to determine other important properties such as void ratio or porosity.(6)

Shear Strength: Typical values of the angle of internal friction of most waste rock sources exceed 35 degrees and contribute to relatively high bearing capacity and stability.

Mill Tailings

Some of the properties of mill tailings that are of particular interest when mill tailings are used in embankment or fill applications include gradation, particle shape and texture, moisture-density characteristics, and unit weight. The chemical composition of the tailings should also be known prior to its use. It is difficult to definitively characterize representative samples of mill tailings materials because of the number of sources and variations in the degree of processing that can be encountered.

Gradation: Typically, mill tailings range from sand to silt-clay in particle size, with 40 to 90 percent passing a 0.075 mm (No. 200) sieve. They are usually disposed of in slurry form by pumping into large retention areas or settlement ponds.(7) The coarser, sand-size fractions, if any, of mill tailings are more highly recommended for embankment construction. Mill tailings can be classified prior to disposal or blended with coarser materials, such as gravel, to bring the overall fines content to an acceptable range, preferably less than 35 percent passing a .0075 mm (No. 200) sieve.

Shape/Texture: Mill tailings consist of hard, angular, siliceous particles.

Moisture-Density Characteristics: With the possible exception of iron ore or taconite tailings, most mill tailings have an optimum moisture content in the range of 10 to 18 percent. The maximum dry density of most tailings is in the range of 1600 to 2025 kg/m^3 (100 to 125 lb/ft^3).(8)

Unit Weight: Iron ore and taconite tailings typically have high unit weight values, up to as high as 2700 kg/m^3 (170 lb/ft^3). The unit of weight of most other tailings sources is expected to range from 1500 to 2000 kg/m^3 (90 to 135 lb/ft^3), which is comparable to that of most natural aggregates.(7)

Coal Refuse

Some of the properties of coarse coal refuse that are of particular interest when coarse coal refuse is used in embankment or fill applications include gradation, particle shape/ texture, moisture-density characteristics, strength, permeability, durability, resistance to wetting/drying, and frost susceptibility.

Gradation: Coarse coal refuse, which is greater than 4.75 mm (No. 4 sieve), is a well-graded material (can vary in size from 100 mm (4 in) to 2 mm (No. 10 sieve)) consisting mainly of slate or shale with some sandstone or clay. Most coarse refuse contains particles that may break down under compaction equipment, resulting in a finer gradation following placement.

Shape/Texture: Coal refuse is composed mainly of flat slate or shale particles with some coal, sandstone, and clay intermixed. Such particles may weather or break down easily.

Moisture-Density Characteristics: Based on available data, the optimum moisture content of coarse coal refuse is likely to range from 6 to 15 percent and its maximum dry density may vary from 1300 to 2000 kg/m^3 (80 to 120 lb/ft^3).(3,5)

Shear Strength: The shear strength of coarse coal refuse can be highly variable. The angle of internal friction values for coarse coal refuse have been reported to be between 18 and 42 degrees.(9) The shear strength of coal refuse is usually lower than that obtained for other granular materials with similar properties, but can be increased by proper compaction.(5,9,10) Previous experience with coal refuse usage as a construction material has demonstrated that the shear strength of the refuse is acceptable if proper compaction is achieved during construction.(9,11)

Permeability: The permeability of coarse coal refuse can also be highly variable and should be determined for each particular refuse source. It is related to the composition of the refuse, its degradation during compaction, and the degree of compaction.(9,12) The permeability of coarse coal refuse is less than that of other granular materials with a similar grain size distribution. Conventional formulas for estimating the permeability of coal refuse on the basis of size distribution and uniformity are not applicable for this material.(13)

It is preferable to attain lower permeability to reduce the air circulation, and void ratio and to eliminate spontaneous combustion, oxidation of pyrites, and acidic leachate.(14) The permeability can decrease rapidly when the percentage of particles minus 4.75 mm (No. 4 sieve) increases. However, at some point, as more minus 4.75 mm is added, the coarse particles may be displaced or pushed apart, creating higher permeability.(15)

Durability: If durability is a concern in the top layers of an embankment, fly ash can be added to the refuse to neutralize acidity of the refuse, increase its moisture-holding capacity and pore space volume, and reduce its erodability.(4) Lime and/or cement used as a binding agent with the fly ash produces a pozzolanic reaction, providing added strength and durability to the coarse coal refuse.(9)

Resistance to Wetting/Drying: Coal refuse begins weathering immediately after it has been placed in an embankment. Increases in the soluble sulfur content can induce oxidation of the pyrite. However, once the material is sealed within the embankment, oxidation is limited and weathering is greatly reduced. Water penetration is virtually eliminated, along with the degradation resulting from intermittent wetting and drying.

Frost Susceptibility: The top layers of coal refuse (especially burnt refuse) may be susceptible to damage from frost. Frost damage can be reduced or eliminated by the addition and mixing of cement into the top 1 meter (3 ft) of refuse.(16)

DESIGN CONSIDERATIONS

Waste Rock and Mill Tailings

The design requirements for waste rock or mill tailings in embankment construction are the same as for conventional aggregates or soils. These materials must meet appropriate sizing requirements and satisfy standard Proctor moisture-density criteria according to AASHTO T99.(17)

Structural design procedures to be employed for embankment or fill construction containing waste rock or mill tailings are essentially the same as design procedures that are used for conventional embankment materials. An analysis of the slope stability and consolidation characteristics of the embankment must be completed prior to construction. Some tailings sources may have an excessive amount of fines (greater than 35 percent passing the 0.075 mm (No. 200) sieve) which could necessitate prior classification or separation and use of only the coarse fraction of the tailings in an embankment or fill.

Coal Refuse

The design requirements for coarse coal refuse in embankment or fill construction are essentially the same as for conventional aggregates or soils. However, tests for standard Proctor moisture-density and spontaneous combustion potential should be carried out for all coal refuse that is considered for use in highway construction. Leaching and swelling indexes, porosity, freeze-thaw tests and wet-dry swelling tests are also required. Water-soluble sulfate testing methods/ specifications for determining the amount of sulfate found in coarse coal refuse and measures used to overcome such sulfate content are available from the British National Coal Board.(18)

Design procedures for embankments or fill containing coal refuse are the same as design procedures for conventional embankment materials. Slope stability and settlement analyses should be conducted to ensure that the coal refuse embankment is stable at the design slope and will not settle excessively. The potential for weathering and frost heave must also be considered.

Coal refuse for use in embankments should be tested in accordance with AASHTO test methods T234(19) and T236(20) to determine the shear strength characteristics of the material tested. AASHTO T216(21) and T193(22) are also used to determine the consolidation characteristics of the refuse and evaluate its subgrade bearing capacity.(4)

CONSTRUCTION PROCEDURES

Material Handling and Storage

Waste Rock and Mill Tailings

The same methods and equipment used to store or stockpile conventional aggregates are applicable for waste rock and mill tailings.

Coal Refuse

Prior to using the refuse to construct embankments or fills, the bank should be cleaned or processed to recover the residual coal or combustible matter. This ordinarily involves a screening of the refuse, which also removes oversize and deleterious materials.

Placing and Compacting

Waste Rock

The same methods and equipment used to place and compact conventional rock as embankment base or foundation material can be used for the placement of mine waste rock. Compaction operations and methods must be visually inspected on a continuous basis to ensure that the specified degree of compaction can be achieved, or that there is no movement under the action of compaction equipment. The construction of embankment bases or foundations containing rock or oversize materials usually requires a method specification, which describes how to place and compact such materials, but does not include test methods or acceptance criteria.

Mill Tailings

No modifications to normal construction equipment or procedures are needed for placing and compaction of mill tailings, except that mill tailings may need to be dried to near optimum moisture content prior to placement and compaction.

Coal Refuse

No modifications to normal construction equipment or procedures are needed, except that material breakdown under compaction equipment requires more repetitive testing in the field. The key to the success of placing coarse coal refuse is in proper compaction. Proper compaction of coal refuse reduces air voids to less than 10 percent, and can reduce the permeability to less than 10^{-5} to 10^{-6} cm/sec, which is very low. Well-compacted material is sufficiently dense for embankment construction with minimal potential for ignition because of spontaneous combustion.(5)

Quality Control

Waste Rock and Mill Tailings

The same test procedures used for conventional aggregate are appropriate for waste rock and mill tailings, although waste rock may have particles too large for certain in-place density tests. The same field test procedures used for conventional aggregate are recommended for embankment and fill applications when using waste rock or mill tailings. Standard laboratory and field test methods for compacted density are given by AASHTO T191,(23) T205,(24) T238,(25) and T239.(26)

Coal Refuse

Strict compaction control testing is necessary when building an embankment with coarse coal refuse. One of the best methods for controlling the compaction of coarse coal refuse embankments is to first place a test strip to determine the most appropriate compaction equipment and number of passes to ensure adequate compaction. The test strip will also assist in identifying the degree of particle breakdown and its effect on moisture-density characteristics for different types of compaction machinery.

The quality control test procedures described above for waste rock and mill tailings are also applicable to coarse coal refuse, except that some refuse particles may be too large for certain in-place density tests.

Special Considerations

A determination of the sulfate levels that may be leached from coarse coal refuse is required in order to design for the protection of any adjacent concrete structures. The pH value of the refuse in water should also be determined for proper selection of type of underdrain or other drain pipes.

UNRESOLVED ISSUES

Waste Rock and Mill Tailings

General specifications and design methods should be developed for waste rock and/or mill tailings use in embankment or fill applications by those agencies where such materials are logistically available in large quantities and are suitable for embankment or fill use.

There is also a need to determine whether specific sources of such materials are environmentally suitable for embankment construction, particularly some sources of mill tailings. Engineering data are needed on the design properties and performance of waste rock and/or mill tailings that have been successfully used in highway embankment or fill applications.

Coal Refuse

There is a need to further evaluate environmental concerns regarding the potential for acidic leachate from coarse coal refuse used in embankments. The production of such leachate is caused by the oxidation of pyrite and marcasite with presence of high sulfur content. If acidic leachate were to be produced over time, it would contaminate ground water, adversely impact the ecosystem, and cause deterioration or corrosion of underdrains or other drain pipes.

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ORIGIN

Municipal solid waste (MSW) combustor ash is the by-product that is produced during the combustion of municipal solid waste in solid waste combustor facilities. In most modern mass burn solid waste combustors, several individual ash streams are produced. They include grate ash, siftings, boiler ash, scrubber ash and precipitator or baghouse ash. Figure 10-1 presents a cross-section of a modern mass burn waste combustor with energy recovery, showing where each of the ash streams is produced.

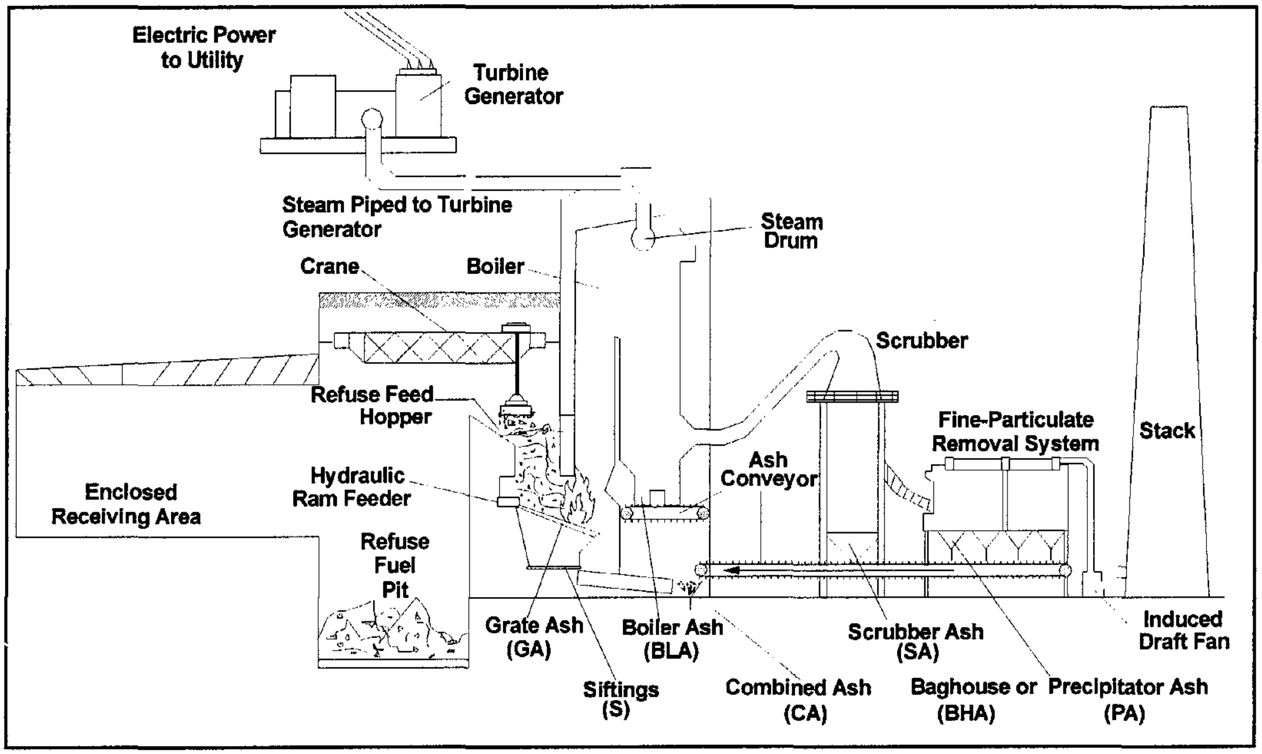

Figure 10-1. Mass burn waste-to-energy facility-typical cross section and ash streams.[(2)]

At the present time in the United States., typically all of the ash streams are combined. This combined stream is referred to as combined ash. The term bottom ash is commonly used to refer to the grate ash, siftings and, in some cases, the boiler ash stream. The term fly ash is also used and refers to the ash collected in the air pollution control system, which includes the scrubber ash and precipitator or baghouse ash. In Europe, most facilities separate and separately manage the bottom ash and fly ash streams.

Bottom Ash

Approximately 90 percent of the bottom ash stream consists of grate ash, which is the ash fraction that remains on the stoker or grate at the completion of the combustion cycle. It is similar in appearance to a porous, grayish, silty sand with gravel, and contains small amounts of unburnt organic material and chunks of metal. The grate ash stream consists primarily of glass, ceramics, ferrous and nonferrous metals, and minerals. It comprises approximately 75 to 80 percent of the total combined ash stream.

Boiler Ash and Fly Ash

Boiler ash, scrubber ash, and precipitator or baghouse ash consist of particulates that originate in the primary combustion zone area and are subsequently entrained in the combustion gas stream and carried into the boiler and air pollution control system. As the combustion gas passes through the boiler, scrubber, and precipitator or baghouse, the entrained particulates stick to the boiler tubes and walls (i.e., boiler ash) or are collected in the air pollution control equipment (i.e., fly ash), which consists of the scrubber, electrostatic precipitator, or baghouse. Ash extracted from the combustion gas consists of very fine particles, with a significant fraction measuring less than 0.1 mm (No. 140 sieve) in diameter. The baghouse or precipitator ash comprises approximately 10 to 15 percent of the total combined ash stream.

Approximately 29.5 million metric tons (32.5 million tons) of solid waste is combusted annually at approximately 160 municipal waste combustor plants in the United States.,(1) generating approximately 8 million metric tons (9 million tons) of residual or ash.(2)

There are two basic types of solid waste combustors in operation in the United States today - mass burn facilities and refuse derived-fuel (RDF) facilities. Mass burn facilities manage over 90 percent of the solid waste that is combusted in the United States. Mass burn facilities are designed to handle unsorted solid waste, whereas RDF facilities are designed to handle preprocessed trash. The ash produced at RDF facilities, where the incoming municipal solid waste stream is shredded and presorted to remove ferrous metal and in certain cases nonferrous metal prior to combustion, can be expected to have different physical and chemical properties from ash generated at mass burn facilities.

There are also significant differences between ash generated at modern waste-to-energy facilities and that generated at older facilities. Newer facilities, with improved furnace designs, generally achieve better burnout and have reduced organic content in the ash product. Due to air pollution control requirements in newer facilities, lime or a lime-based reagent is introduced into the pollution control system to scrub out acid gases from the combustion gas stream. This produces a fly ash that contains both reacted and unreacted lime. Older facilities without acid gas scrubbing do not have lime in their fly ash. Finally, newer facilities with improved air pollution control equipment (e.g., baghouses) are better able to capture the finer particulate materials and trace contaminants, which many of the older facilities usually release into the air. It also is likely that, in the future, more stringent air pollution control requirements (e.g., mercury and NO_x control) will further alter both the physical and chemical properties of fly ash streams.

There are no specific trade or industrial groups associated with incinerator ash recycling in the United States, but additional information can be obtained from the following municipal waste combustor trade association:

Integrated Waste Services Association
1133 21st Street, N.W., #205
Washington, D.C. 20036

CURRENT MANAGEMENT OPTIONS

Recycling

At the present time most operating facilities in the United States recover the ferrous metal fraction present in MSW combustor ash, which can comprise up to 15 percent of the total ash fraction. Only a very small fraction (less than 5 percent) of the nonferrous fraction of the ash generated in the United States is recovered and utilized. Most of the ash is used as a landfill cover material. There is some commercial use of ash in road paving applications presently ongoing in Tennessee.

In some European nations (e.g., The Netherlands and Denmark), more than one-half of the bottom ash generated by municipal waste combustors is used in construction applications. Lesser percentages are used in West Germany and France. In Europe the most common application is the use of ash as a granular road base material.(3)

In the United States and Japan, numerous studies in recent years have focused on the potential for using processed bottom ash and combined ash as an aggregate substitute in asphalt concrete, Portland cement concrete, and as an aggregate in stabilized base applications.

Although neither federal nor most state regulations categorically restrict the use of MSW combustor ash (as long as the ash is determined to be nonhazardous in accordance with regulatory testing criteria), the presence of trace metals, such as lead and cadmium, in MSW combustor ash, and concern over leaching of these metals, as well as the presence of dioxins and furans in selected ash fractions (fly ash), has led many regulatory agencies to take a cautious approach in approving the use of MSW combustor ash as a substitute aggregate material.

Disposal

At the present time in the United States almost all of the annual 8 million metric tons (9 million tons) of ash produced is landfilled. This is in sharp contrast to the aforementioned European practice.

MARKET SOURCES

MSW combustor ash is generally managed by the waste-to-energy facility operator on behalf of the local municipality or authority that owns the facility. The final disposition of ash is usually the responsibility of the municipality or authority. As a result, ash for recycling purposes could normally be obtained by contacting the municipality or authority responsible for the facility.

The properties of the ash that may be made available for market will depend on the ash stream (e.g., combined, bottom or grate ash) that is proposed for use. In most cases combined ash contains excess unreacted lime that has been added as an acid gas treatment reagent and as a treatment additive to reduce the leachability of trace metals that are present in the residue. Combined ash, which contains the air pollution control system residues, typically has higher concentrations of volatile metals (e.g., lead, cadmium, zinc) than bottom ash. Bottom ash is usually lime free and contains fewer fines. It is the preferred material for recycling in Europe where the boiler ash is also segregated from the bottom ash prior to bottom ash use.

In addition to the type of ash, the quality of ash received from a given facility will depend in great part on the processing equipment at the facility. A wide range of processing systems have been used to produce an ash-aggregate material from unprocessed residue. The most basic process consists of ferrous metal removal followed by screening of the residue, generally to a minus 19 mm (3/4 in) material, to create a sandy, granular product. Many waste combustors are presently incorporating not only ferrous removal equipment, but nonferrous removal to recover valuable aluminum and copper from the residue.

Ferrous and nonferrous metal removal, screening and, in some cases, air classification can assist in producing a sandlike, metal-free, low organic content product.

To reduce the fines content of combustor residues, pelletizing processes using Portland cement as a binding agent have been proposed and applied(4,5) to improve the engineering and environmental characteristics of incinerator ash.(6) Vitrification, which is a high-temperature process designed to melt and subsequently cool the ash, has been proposed as a potential processing strategy. There are a number of commercial-sized ash vitrification systems currently in operation in Japan.(7) The high cost of vitrification, due primarily to the energy and facilities required to heat and melt the ash, tends to discourage the use of this technology in the United States.

HIGHWAY USES AND PROCESSING REQUIREMENTS

Asphalt Paving

Municipal waste combustor ash has been tested for use as an aggregate substitute in asphalt paving mixes, where it has performed in a satisfactory manner, particularly in base or binder course applications. In this application, the ash is used to replace the sand-size or fine aggregate portion of the mix. In most cases, processed ash that is screened to less than 19 mm (3/4 in) with ferrous and nonferrous metal removal can be introduced to replace anywhere from 10 to 25 percent of the natural aggregate normally present in the mix for surface course applications and up to 50 percent for base course applications.

Granular Base, Fill, and Embankments

Municipal waste combustor ash (grate ash) has been used as a granular base in road construction, as a fill material, and as an embankment material in Europe for almost two decades. The use of ash in granular base and fill applications in the United States has been limited primarily to demonstrations.

In granular base or embankment applications, properly processed ash (i.e., screened to less than 25 to 38 mm (1 to 1-1/2 in) and metal removed) can be either blended or used alone in these applications. Ash can also be stabilized with Portland cement or lime to produce a stabilized base material.

MATERIAL PROPERTIES

During the 1970's and 1980's a number of comprehensive investigations were undertaken to characterize the properties of municipal waste combustor ash. (See References 8,9,10,11.) Most of the data from these early investigations reflect the characteristics of ash from batch-fed or older continuous flow grate designs that are unlike the modern, high-efficiency energy recovery combustors in operation today. During the past few years there have been a number of comprehensive investigations that have characterized the properties of combined and bottom ash residues generated from these newer facilities.(12,13)

Physical Properties

Table 10-1 presents a list of data for some typical physical properties of municipal waste combustor combined and bottom ash that were obtained from two recent comprehensive investigations in which the physical properties of both bottom and combined ash were characterized.

Table 10-1. Selected physical properties of municipal solid waste combustor ash.

Property	Bottom Ash	Combined Ash
Bulk Specific Gravity Fine (<No. 4 sieve) Coarse (>No. 4 sieve)	1.70 - 1.81(12) 1.50 - 2.22(13) 2.11 - 2.23(11) 1.93 - 2.44(12)	1.86 - 2.03(12) 1.96 - 2.24(12)
Absorption (%) Fine (<No. 4 sieve) Coarse (>No. 4 sieve)	12.0 - 17.0(11) 4.1 - 4.7(11)	4.8 - 14.8(12) 3.6 - 10.0(12)
Moisture Content (% Dry Wt)	29 - 66(11) 22 - 62(12)	17 - 76(12)
Unit Weight, kg/m^3 (lb/ft^3)	960 - 1400 (60-86)(11)	990-1170 (62-73)(12)
Loss on Ignition (%)	6.4(12) 3.7(11) 1.5(14)	2.5 - 13.5(12)
Gradation (% Passing) Fine Fraction, <4.75 mm (No. 4 sieve) Silt Fraction, <0.075 mm (< No. 200 sieve)[1]	50 - 70(11) 42 - 62(12) 60 (13) 9 - 16 (11) 2 - 6 (12) 2 (13)	50 - 70(12) 15 - 20(12)
Maximum Density, kg/m^3 (lb/ft^3)	1260 - 1570 (79 - 98)(11) 1710 - 1760 (107-110)(12)	1260 - 1730 (79-108)(12)
Proctor Compacted Permeability (cm/sec)	Approx. 10^{-3} to 10^{-4} (14,15)	Approx . 10^{-6} to 10^{-9} (16)

1. Note: Higher 0.075 mm (No. 200) values were obtained in wash sieve tests.

The data indicate that municipal solid waste combustor ash is a relatively lightweight material compared with natural sands and aggregate. The bulk specific gravities that were reported range from 1.5 to 2.2 for sand-size or fine particles and 1.9 to 2.4 for coarse particles, compared with approximately 2.6 to 2.8 for conventional aggregate materials.

Combustor ash is highly absorptive with absorption values ranging from 5 to 17 percent for fine particles and from about 4 to 10 percent for coarse particles. Conventional aggregates typically exhibit absorption values of less than 2 percent.

Prior to exiting a municipal solid waste combustor, the ash is quenched, resulting in the high moisture content values listed in Table 10-1. This high moisture content is due the quenching and relatively high porosity and absorptive nature of combustor ash.

The relatively low unit weights further underscore the lightweight nature of combustor ash, and the loss on ignition values suggest that the ash can contain relatively high levels of organics compared with conventional aggregates.

Combustor ash is primarily a sandy material with the major fraction passing a 4.75 mm (No. 4) sieve. Ash also contains a relatively high minus 0.075 mm (No. 200 sieve) silt fraction.

Chemical Properties

Table 10-2 lists the major chemical constituents present in MSW combustor ash.

Table 10-2. Typical chemical composition (percent) of MSW combustor ash.

Constituent	Bottom Ash	Combined Ash
Silicon	16.8 - 20.6(12) 18.3 - 27.4(13)	13.8 - 20.5(12)
Calcium	7.15 - 7.69(12) 5.12 - 10.3(13)	5.38 - 8.03(12)
Iron	2.11 - 9.35(12) 5.64 - 11.5(13)	2.88 - 7.85(12)
Magnesium	1.05 - 1.18(12) 0.19 - 1.07(13)	0.90 - 1.84(12)
Potassium	0.84 - 1.02(12) 0.72 - 1.16(13)	0.84 - 1.15(12)

Table 10-2. Typical chemical composition (percent) of MSW combustor ash (continued).

Constituent	Bottom Ash	Combined Ash
Aluminum	4.77 - 5.55(12) 3.44 - 6.48(13)	3.26 - 5.44(12)
Sodium	3.51 - 4.10(13) 2.02 - 4.80(13)	2.00 - 4.62(12)

The most abundant elements in municipal waste combustor ash are silica, calcium, and iron. Although ash composition can be expected to vary from facility to facility, these elements are present within relatively predictable ranges. This is reflected in the results presented in Table 10-2.

The presence of a relatively high salt content and trace metal concentrations, including such elements as lead, cadmium, and zinc, in municipal waste combustor ash (compared with conventional aggregate materials) has raised concerns in recent years regarding the environmental acceptability of using ash as an aggregate substitute material.

The presence of calcium and other salts in relatively high concentrations in MSW combustor ash makes the ash susceptible to hydration and/or cementitious reactions (particularly in the combined ash, which contains unreacted lime) and subsequent swelling. The presence of free aluminum in the ash when combined with water can also result in the formation of hydrogen gas. In addition, the high salt content also suggests that ash could be corrosive if placed in contact with metal structures, and that it would likely interfere with curing and strength development if used in Portland cement concrete.

Mechanical Properties

Table 10-3 lists some typical mechanical properties associated with municipal waste combustor ash.

The data suggest that MSW combustor ash has relatively poor durability characteristics as measured by the Los Angeles. Abrasion Test. Los Angeles abrasion values presented are above or at the limits normally specified for the use of coarse aggregates in asphalt paving applications. Reported soundness values are generally within typical specifications, suggesting that ash is not highly susceptible to freeze-thaw cycles. California Bearing Ratio (CBR) results for both bottom and combined ash are similar to those that could be anticipated for a well-graded crushed stone, suggesting excellent bearing capacity: reported friction angle data suggest a material with good lateral stability.

Table 10-3. Typical mechanical properties of MSW combustor ash.

Property	Bottom Ash	Combined Ash
Los Angeles Abrasion (%)		
Grading B	47.3(13) 55 - 60(12)	44 - 52(12)
Grading C	43.4(13) 41 - 47(12)	36 - 45(12)
Sodium Sulfate Soundness (%)		
Fines Fraction (<No. 4 sieve)	10.4 - 14.3(13) 1.6 - 2.7(12)	2.2 - 4(12)
Coarse Fraction (> No. 4 sieve)	2.5 - 2.8(13) 2.9(12)	3.5(12)
California Bearing Ratio (CBR) (%)		
0.1 in penetration	74 - 86(13) 90 - 155(12)	95 - 140(12)
0.2 in penetration	104 - 116(13)	
Angle of Internal Friction (deg.)	40 - 45(14,15)	

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INTRODUCTION

Municipal solid waste (MSW) combustor bottom ash and combined ash that has been processed to remove ferrous and nonferrous metals and to achieve the appropriate particle size gradation can be blended with other aggregates for use in an asphalt paving mix. Due to the larger fraction of finer, grain-sized material in processed MSW combustor ash than coarse, grain-sized material, the ash is primarily used as a substitute for fine aggregate in a paving mix. Although up to 50 percent, by weight of aggregate, has been used in some test pavements, it is recommended that the substitution rated be limited to 25 percent ash in binder or base course and 15 percent or less in surface mixes to ensure satisfactory paving material production and field performance.

PERFORMANCE RECORD

There is no large-scale commercial use of municipal waste combustor ash in asphalt paving mixes in the United States at the present time.

During the 1970's and early 1980's at least six test pavements containing municipal solid waste (MSW) combustor ash were installed under Federal Highway Administration (FHWA) sponsored programs. Base course test sections were placed in Baltimore,(1) Houston,(2) and Washington, DC.(3) Wearing or surface course test sections were placed in Delaware County, PA, Philadelphia, PA, and Harrisburg, PA.(4) In 1980 a binder and surface course section was placed in Lynn, MA.(5) More recently (during the past 10 years) test pavements have been placed in Shelton, CT,(6) Tampa, FL,(7) Rochester, MA,(8) Laconia, NH,(9) and Elizabeth, NJ.(10) A listing of specific design details associated with many of the referenced test pavement demonstrations is presented in Table 10-4.

Table 10-4. MSW combustor ash paving demonstrations.

Project (Date)	Ash Type	Ash Fraction (%)	Asphalt Cement (%)	Lime (%)	Pavement Course
Houston, TX (1974)	Combined Ash	100	9.0	2.0	Base
Philadelphia, PA (1975)	Combined Ash	50	7.4	2.5	Surface
Delaware Co., PA (1975)	Combined Ash	50	7.0	2.5	Surface
Harrisburg, PA (1975)	Combined Ash	50	7.0	2.5	Surface
Harrisburg, PA (1976)	Combined Ash (vitrified)	100	6.7	0.0	Surface

Table 10-4. MSW combustor ash paving demonstrations (continued).

Project (Date)	Ash Type	Ash Fraction (%)	Asphalt Cement (%)	Lime (%)	Pavement Course
Washington, DC (1977)	Combined Ash	70	9.0	2.0	Base
Lynn, MA (1979)	Combined Ash	50	6.5	2.0	Binder & Surface
Tampa, FL (1987)	Combined Ash (pelletized)	5 - 15	-	-	Base & Surface
Rochester, MA (1992)	Bottom Ash (dry RDF process)	30	-	-	Base & Surface
Laconia, NH (1993)	Grate Ash	50	7.0	-	Binder
Elizabeth, NJ (1996)	Bottom Ash	15	5.1	-	Surface

All of the 1970 pavement demonstrations were considered successful by FHWA, with the exception of the Harrisburg pavement where considerable stripping was reported during the first year. In general, the results of the early FHWA test demonstrations suggested that municipal waste combustor ash could be mixed, placed, and compacted using conventional bituminous construction equipment.

Difficulties were noted with residues that contained high organic content (measured as loss on ignition), compared with residues with low organic content. Residues having LOI's greater than 10 percent exhibited high and uneven absorption of asphalt during the asphalt production process. High asphalt demand and dusting during drying was attributed to the high fines content in the ash. The need for close temperature control at the asphalt plant to control the drying process, particularly with high moisture content ash, was also noted.(5)

Base course applications were generally considered to be better suited for use as ash pavements than wearing coarse applications.

The results of more recent demonstrations, conducted during the past 10 years, found ash sections in general to be comparable in performance to conventional mixes; however, some difficulty in the asphalt production process because of baghouse clogging(9) and high ash moisture content(10) were reported. A breakdown in ash particles to a finer graded product during the production process was also reported.(9,10)

During the asphalt production process, the introduction of aggregates blended with a large fraction of ash (that contains a high moisture and fines content) could result in potential operational problems. This includes lower plant throughput rates to provide greater time for drying and potential clogging of the asphalt plant baghouse with excessive fines from the ash.

Asphalt pavements incorporating municipal waste combustor ash can be expected to benefit from the low unit weight of the ash compared with conventional aggregate and the resultant higher yield expressed in terms of volume per ton. Pavements that contain higher percentages of ash require higher percentages of asphalt binder (cement) compared with conventional aggregate mixes. This results from the highly absorptive characteristics of ash particles. Due to the relatively low durability of ash particles compared with that of natural aggregates, and the high percentage (approximately 20 to 30 percent) of glass that is present in ash, the introduction of high percentages of ash into wearing course mixes could result in ravelling or stripping problems.

MATERIAL PROCESSING REQUIREMENTS

Segregation of Ash Streams

The separation of the coarse ash particles (grate ash) from the fine ash particles (fly ash and the boiler ash) at the combustion facility, and the use of the coarse ash, is a preferable ash collection strategy. From a paving perspective the reduction in fines would help reduce the highly absorptive fine fraction and also help to alleviate potential baghouse clogging problems during the asphalt production process.

Screening

Screening to a minus 19 mm (3/4 in) top size is necessary to produce an aggregate substitute material that can meet most gradation specifications. Screening to a smaller top size, such as minus 12.7 mm (1/2 in), is more desirable to produce a material with a lower plus 12.7 mm (1/2 in) fraction, since this fraction can consist of weak particles (clinkers) that readily break down during handling. Screening of ash with a relatively high moisture content to a minus 12.7 mm (1/2 in) size, however, could clog screening equipment or slow screening throughput rates.

Ferrous and Nonferrous Metal Removal

Ferrous removal using magnetic separators is mandatory, and nonferrous metal removal using eddy current separators is preferable to produce a metal-free nonreactive ash product. The presence and oxidation of ferrous metal in surface pavements could result in popouts.

Blending

To satisfy the gradation requirements of AASHTO T27 (11) municipal waste combustor ash must be blended with conventional aggregate.

Vitrification

High temperature melting processes that vitrify the ash have been commercially used in Japan and have been demonstrated in the United States (12,13) The process of vitrification can produce a glass product that can alleviate many of the aforementioned problems associated with ash fines and moisture. Such processing, however, is energy intensive and costly and has not been adopted in the United States.

ENGINEERING PROPERTIES

Some of the engineering properties of MSW combustor ash that are of particular interest when MSW combustor ash is used as aggregate in asphalt paving applications include gradation, unit weight, durability, moisture content, and absorption.

Gradation: Minus 19 mm (3/4 in) municipal waste combustor ash is a well-graded material. Approximately 60 percent of both bottom and combined ash falls into the category of a fine aggregate material. The measured silt content (minus 0.075 mm (No. 200 sieve) fraction) of MSW combustor ash can be expected to range from 5 to 15 percent. The well-graded nature of minus 19 mm (3/4 in) ash makes it a relatively easy product to blend in high percentages into most paving mixes, where 50 percent of the natural aggregate can be readily replaced with ash in most base course mixes (and still comply with gradation specifications). For use in hot mix asphalt, MSW combustor ash must meet the same gradation requirements as conventional aggregate as per AASHTO T27.(11)

Unit Weight: The lower unit weight of MSW combustor ash, which is approximately 965 to 1290 kg/m^3 (60 to 80 lb/ft^3), can be expected to result in higher asphalt paving yields (paved area per mass of asphalt), when compared with natural aggregate paving yields.

Durability: MSW combustor ash exhibits marginal durability, as measured by the Los Angeles Abrasion test (40 to 50 percent). Breakdown of coarse particles can be expected in handling and asphalt production, which could potentially reduce the quality of the mix.

Moisture Content: MSW combustor ash moisture content can vary a great deal, ranging from approximately 30 to 60 percent on a dry weight basis. This moisture content, as previously noted, can be expected to impact asphalt production operations.

Absorption: MSW combustor ash is a highly absorptive material, with absorption values ranging from 5 to 17 percent. This manifests itself in asphalt cement requirements that could be significantly higher (10 to 20 percent) than that required when conventional aggregate materials are used.

Some of the asphalt mix properties that can be affected by the use of MSW combustor ash include mix stability and stripping (moisture susceptibility).

Stability: Stability of mixes has been reported to be comparable to natural aggregate mixes.(9) These results are expected if municipal waste combustor ash is used to replace primarily the fine aggregate fraction of the mixes.

Stripping: During demonstration programs in the 1970's, hydrated lime was added to MSW combustor ash as an antistripping agent in surface courses. During demonstrations in the late 1980's and 1990's, no hydrated lime was added. When ash is used as a fine aggregate substitute and mix percentages are kept low (approximately 15 percent), stripping problems should be minimal. Higher percentages may warrant the addition of an antistripping agent.

DESIGN CONSIDERATIONS

Mix Design

Asphalt mixes containing MSW combustor ash can be designed using standard laboratory procedures. Care must be taken, however, to ensure that the asphalt cement content is adequate to account for the high absorption of ash particles during the mix design process. Recent work has suggested that Marshall mix design methods could lead to overestimating the required asphalt content of the mix and could result in subsequent pavement failure due to rutting. The use of a Gyratory Test Machine as specified in ASTM D3387 has been proposed as an alternative for preparation of the mix, using gyratory compactibility and stability indices to determine the optimum asphalt content.(9)

Lower ash contents may be more suitable in paving mixes to reduce the asphalt cement requirements resulting from the introduction of a large fraction of highly absorptive ash particles into the mix.(14) As long as percentages of ash introduced into a mix remain low (less than 20 percent), additional asphalt cement requirements should be reasonably low. Lower ash contents in surface mixes can also eliminate the need for antistripping agents such as hydrated lime.

No special accommodation is required for aggregate gradations and conventional hot mix gradations can be used; however, it is advisable to anticipate some measurable breakdown of ash particles during handling. This could increase the fine aggregate and silt fraction of the mix during the production process and open up new, uncoated absorptive particles resulting in unanticipated asphalt demand.

Structural Design

Conventional AASHTO pavement structural design methods are appropriate for asphalt pavements incorporating MSW combustor ash in the mix.

CONSTRUCTION PROCEDURES

Material Handling and Storage

In some European countries, where MSW combustor bottom ash is used as a granular base material, the ash is stored from 30 days to 6 months prior to use.(15) This storage period provides time for potentially hydratable and expansive salts to react prior to the use of the material in a construction application. The use of combined ash that may contain free lime could further aggravate this problem. Storage of ash for at least 30 days in asphalt paving applications is probably adequate when using 10 to 20 percent ash in the mix. Longer periods of storage may be needed if higher percentages of ash are introduced into a mix.

Mixing, Placing, and Compacting

The same methods and equipment used for conventional asphalt production are applicable to paving mixes containing MSW combustor ash. During asphalt production, special care must be provided to control plant temperature, which could be impacted by the moisture content of the ash. This will probably necessitate a reduction in plant throughput rates. Excessive fines in the ash and high ash contents (greater than 20 percent) could result in excessive carry-over of fines into the baghouse. This will be more problematic in batch plants where the ash will most likely be dried by itself prior to storage in hot bins.

The same methods and equipment used for placing and compacting conventional pavement are applicable to asphalt pavements containing MSW combustor ash.

Quality Control

The same field testing procedures used for conventional hot mix asphalt mixes should be used for mixes containing MSW combustor ash. Mixes should be sampled in accordance with AASHTO T168,(16) and tested for specific gravity in accordance with ASTM D2726, (17) and in-place density in accordance with ASTM D2950.(18)

UNRESOLVED ISSUES

The use of municipal waste combustor ash in hot mix asphalt has yet to be commercialized on a large scale in the United States There are no specifications regarding minimum processing requirements, ash properties, or mix characteristics. In addition, ash contains levels of trace metals (particularly lead) and high soluble salt levels. Potential impacts need to be more fully addressed to ensure that the use of MSW combustor ash does not result in any adverse environmental impacts. Additional data regarding asphalt plant operations and air emission quality, when MSW combustor ash are introduced into a plant, are needed.

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INTRODUCTION

Municipal solid waste (MSW) combustor ash (bottom ash or combined ash) can be used as a granular base material in road construction applications. The high stability of MSW combustor ash provides for good load transfer to the pavement subgrade. Its somewhat marginal durability, however, could result in breakdown during compaction and the relatively high percentage of fines in combustor ash could result in frost susceptibility. The ash must also be stored prior to use to minimize the possibility of any volumetrically expansive hydration reactions from occurring after placement.

PERFORMANCE RECORD

The use of MSW combustor ash as a granular fill material in the United States has been largely limited to its use in a few test demonstrations.(2) In Europe, however, the same material has been in commercial use as a granular base or fill for use in road base and embankment applications for almost two decades. In Denmark, Germany, and The Netherlands, more than 50 percent of the bottom ash generated is used in granular base or fill applications.(1)

In the United States test demonstrations have been undertaken in Texas, Massachusetts, and California.(2) In addition to its use as a granular base, municipal waste combustor ash has also been blended with lime and used or proposed for use as a stabilized base material.(3) A listing of some locations where MSW combustor has been used in road base applications is presented in Table 10-5.

Table 10-5. MSW combustor ash road base/subbase demonstrations.

Project (Date)	Ash Type	Particle Size Ash % in Mix	Site Use
Houston, TX (1974)	Combined Ash	25 mm (1 in), 100% ash	Road base, 150 mm (6 in), 61 m (200 ft) of access roadway
Houston, TX (1977)	Combined Ash	25 mm (1 in), 70% ash	Road base, 114 mm (4.5 in), 122 m (400 ft) to residential street
Los Angeles, CA (1991)	Combined Ash	50 mm (2 in), 12% Portland cement with fly ash; 15% water added to treated mix	Subbase for landfill roads

Table 10-5. MSW combustor ash road base/subbase demonstrations (continued).

Project (Date)	Ash Type	Particle Size Ash % in Mix	Site Use
Massachusetts (1992)	Bottom Ash	No data	Subbase parking lot, up to 2.4 m (8 ft) thick Road base, access road Subbase, access road, up to 0.6 m (2 ft) thick

Although there has been little documented postconstruction monitoring on any of the test demonstrations, all of the demonstrations are believed to have performed in a satisfactory manner.

Some of the more desirable features of MSW combustor ash in granular base applications include its extremely high stability and low unit weight. It is not a highly durable material, however, and is subject to particle size breakdown under heavy equipment load. MSW combustor ash also contains concentrations of trace metals and soluble salts that may warrant some environmental concern.

MATERIAL PROCESSING REQUIREMENTS

Segregation of Ash Streams

In most countries in Europe where ash has been used as a granular base material, the grate ash has been separated from the boiler ash and fly ash. This helps to reduce the fines (minus 0.075 mm (No. 200 sieve)) fraction from the ash, producing a more suitable granular base material. It also eliminates the inclusion of free lime associated with the fly ash fraction, which could produce expansive reactions, and provides for a material with lower trace metal and trace organic content than the combined ash stream.

Ferrous and Nonferrous Metal Removal

Ferrous and nonferrous metal should be removed prior to use. Metal removal is necessary to produce a suitable granular material, because ferrous and some nonferrous metals (such as aluminum) are known to produce adverse reactions. For example, free aluminum that is present in the ash could potentially react with water to form hydrogen gas.

Organic Content

The organic content in the ash should be minimized. In some countries bottom ash samples found to contain greater than 5 percent LOI are unacceptable for use. The organic limitations are primarily the result of concern over gas evolution and subsidence problems.(1) These organic content limitations can normally be met if the combustor is operating efficiently. If the organic content is higher, then additional processing, such as air classification, may be required.

Screening

In some European countries it is recommended that the ash be screened to a maximum grain size of 50 mm (2 in), with less than 10 percent of the total weight less than 0.06 mm (No. 300 sieve) in size.(1)

Aging

It is recommended that bottom ash should be stockpiled for a 1- to 3-month period to allow swelling, hydration, carbonation, and oxidation aging reactions to occur.

ENGINEERING PROPERTIES

Some of the engineering properties that are of particular interest when MSW combustor ash is used in granular base applications include gradation, density, stability, durability, and drainage characteristics.

Gradation: MSW combustor ash must be screened to produce, at a minimum, a minus 19 mm (3/4 in) material and preferably a minus 12.7 mm (1/2 in) material. Larger-sized particles tend to be less granular and typically comprise pieces of ceramic or metal. Processed MSW combustor ash should meet the gradation requirements of AASHTO M147.(4)

Density: The compacted unit weight of processed municipal waste combustor ash is in the range of 1280 to 1760 kg/m^3 (80 to 110 pcf), which is somewhat lower than that of conventional aggregates.(4,5) Maximum density has been reported at moisture contents in the range of 12 to 16 percent, by total weight.(4)

Stability: Minus 19 mm (3/4 in) municipal waste combustor ash is a well-graded material.(5,6) The apparent angularity of the particles and high friction angle (40 to 45°)(7,8) contribute to its high bearing capacity. California Bearing Ratio (CBR) values have been shown to range from approximately 75 to 150 percent, which is similar to crushed stone.(4,9)

Durability: MSW combustor ash is not a highly durable material as measured by the Los Angeles Abrasion test method (values approximately 40 to 60 percent), but does exhibit resistance to freezing and thawing as measured by sodium soundness tests (values generally less than 10 percent).

Drainage: Although compacted bottom ash is a free-draining material (with permeabilities ranging from 10^{-2} to 10^{-4} cm/sec), compacted combined ash, particularly compacted combined ash containing hydrated lime (introduced into the ash through the air pollution control system) is a relatively impermeable material with compacted permeabilities ranging from 10^{-5} to 10^{-7} cm/sec.(6,7,8)

DESIGN CONSIDERATIONS

Structural design procedures for granular base containing processed MSW combustor ash are the same as design procedures for bases containing conventional aggregate. Combined ash with excess lime can be expected to exhibit properties similar to that of a lime-stabilized base material. In such cases AASHTO T99(10) or T180(11) procedures should be used to prepare a mixture with optimum moisture and maximum compacted density. ASTM C593(12) compressive strength and durability testing should be undertaken to assess the properties of the compacted mix.

CONSTRUCTION PROCEDURES

Material Handling and Storage

The same equipment and procedures used to stockpile, handle, place and compact conventional aggregates can be used for processed ash in granular base applications.

MSW combustor ash should probably be stored for at least 3 months prior to use. The relatively low optimum moisture content of ash coupled with the high moisture content of fresh ash suggests that ash be stored, not only to permit aging reactions to occur, but to reduce the moisture content prior to use.

Placing and Compacting

It has been recommended that a minimum 10-ton vibratory roller be used to achieve maximum compaction, and that aged, well-drained ash be used to enable maximum density to be achieved in the field.(13) In addition, due to the marginal durability of the ash, a breakdown in particles toward the fine side can be expected.

Quality Control

The same field test procedures used for conventional aggregate are recommended for granular base applications when using MSW combustor ash. Standard laboratory and field test methods for compacted density are given by AASHTO T191,(14) T205,(15) T238,(16) and T239.(17)

UNRESOLVED ISSUES

The most pressing issue to be resolved relative to the use of incinerator ash in granular base applications is the environmental suitability of using these materials. Although no adverse impacts associated with using these materials in Europe have been reported, the high trace metal and salt contents associated with these residues have raised concerns regarding the environmental suitability of these materials.

Additional work is also needed to address aging requirements and the potential for hydrogen gas formation due to free metal and water reactions.

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ORIGIN

Nonferrous slags are produced during the recovery and processing of nonferrous metal from natural ores. The slags are molten by-products of high temperature processes that are primarily used to separate the metal and nonmetal constituents contained in the bulk ore. When cooled, the molten slag converts to a rocklike or granular material.

The processing of most ores involves a series of standardized steps. After mining, the bulk ore is processed to remove any gangue (excess waste rock and minerals). This processing typically consists of pulverizing the ore to a relatively fine state, followed by some form of gravity separation of the metals from the gangue (using a series of devices including cyclone separators, inclined vibratory tables, and flotation tanks). The refined ore is processed thermally to separate the metal and nonmetal constituents, then further reduced to the free metal. Since most of these metals are unsuitable for use in a pure state, they are subsequently combined with other elements and compounds to form alloys having the desired properties.

In preparation for metal ion reduction (designed to separate the metal from the nonmetal constituents), some nonoxide minerals are often converted to oxides by heating at air temperatures below their melting point ("roasting"). Sulfide minerals, when present (in copper and nickel ore), are converted to oxides in this process. The reduction of the metal ion to the free metal is normally accomplished in a process referred to as smelting. In this process, a reducing agent, such as coke (impure carbon), along with carbon monoxide and hydrogen, is combined with the roasted product and melted in a siliceous flux. The metal is subsequently gravimetrically separated from the composite flux, leaving the residual slag.

The following nonferrous slags are included in these guidelines: copper, nickel, phosphorus, lead, lead-zinc, and zinc. Approximately 3.6 million metric tons (4 million tons) each of copper and phosphorus slag are produced each year in the United States, while the annual production of nickel, lead and zinc slags is estimated to be in the range of 0.45 to 0.9 million metric tons (0.5 to 1.0 million tons).(1)

Copper and Nickel Slags

Copper and nickel slags are produced by: (1) roasting, in which sulfur in the ore is eliminated as sulfur dioxide (SO_2); (2) smelting, in which the roasted product is melted in a siliceous flux and the metal is reduced; and (3) converting, where the melt is desulfurized with lime flux, iron ore, or a basic slag and then oxygen lanced to remove other impurities.

Copper slag that is derived by smelting of copper concentrates in a reverberatory furnace is referred to as reverberatory copper slag.(1)

Phosphorus Slag

Phosphorus slag is a by-product of the elemental phosphorus refining process. The elemental phosphorus is separated from the phosphate-bearing rock in an electric arc furnace, with silica and carbon added as flux materials to remove impurities during the slagging process. Iron, which is added to the furnace charge, combines with phosphorus to form ferrophosphorus which can be tapped off. The slag, which remains after removal of elemental phosphorus and/or ferrophosphorus, is also tapped off.

Lead, Lead-Zinc and Zinc Slags

Lead, lead-zinc, and zinc slags are produced during pyrometallurgical treatment of the sulfide ores. The process includes three operations similar to copper and nickel slag production: (1) roasting, (2) smelting, and (3) converting. Lead and zinc are often related as coproducts in both source and metallurgical treatments, and the various combinations of slags, which include lead, lead-zinc, and zinc, are similarly produced.

Figure 11-1 presents a general schematic depicting the slag production process for copper, nickel, and lead-zinc slags. Figure 11-2 presents a similar diagram for phosphorus slag production.

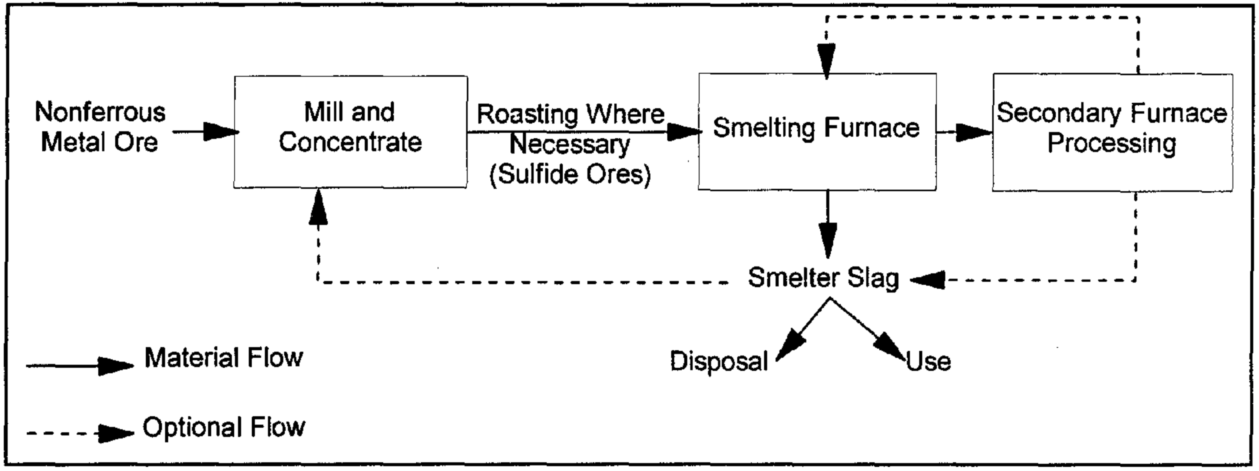

Figure 11-1. General process diagram for copper, nickel and lead-zinc slag production.

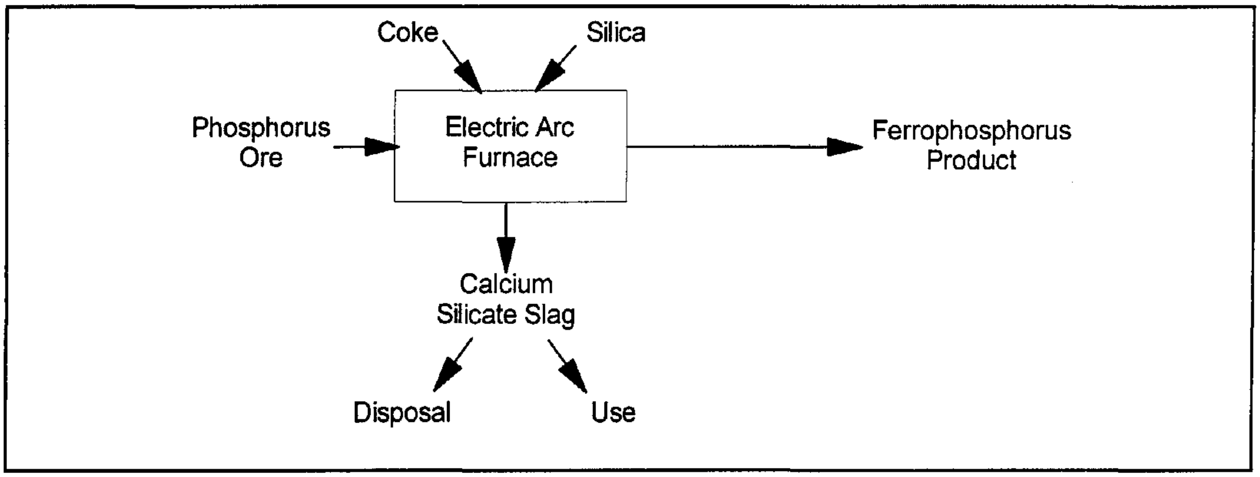

Figure 11-2. General process diagram for phosphorus slag production.

CURRENT MANAGEMENT OPTIONS

Recycling

Copper and Nickel Slags

Copper and nickel slags have been used as granular base and embankment materials, aggregate substitutes in hot mix asphalt, mine backfill materials, railway ballast materials, grit blast abrasives, roofing granule material, and in the manufacture of blended cements (granulated copper and nickel slags).(2,3)

Phosphorus Slag

Phosphorus slag has been used as an aggregate substitute in hot mix asphalt, as a lightweight masonry aggregate, and as cement kiln feed. Granulated phosphorus slag has also been used experimentally in the production of a blended cement product.(4)

Lead, Lead-Zinc, and Zinc Slags

Some zinc slags have reportedly been used in the manufacture of ceramic tiles and as an aggregate substitute in hot mix asphalt.(5,6)

Disposal

Nonferrous slags are produced in a few locations, often remote from potential markets. As a result, nonferrous slags are not well utilized and most of the nonferrous slag produced is disposed of in slag dumps or stockpiles.

MARKET SOURCES

Nonferrous slags, when they are used, are marketed directly by the producers. Slag generation is highly dependent on specific processes and sources; consequently, slag properties can vary between plants and different ore sources, and must be investigated on a case-by-case basis.

Most of the molten nonferrous slag that is produced is dumped into a pit and simply allowed to air cool, solidifying under ambient conditions. A small proportion is granulated, using rapid water and air quenching that results in the production of a vitrified fritlike product. Phosphorus slag is sometimes expanded (solidified with controlled quantities of water, air, or steam, which accelerate the process and increase the cellular nature of the slag), producing a lightweight product.

The cooling rate has a strong influence on the mineralogy and, consequently, the physical and cementitious properties of the nonferrous slags. Granulated slags, which are produced by rapid quenching of the molten slag, are more vitreous and more reactive than similar air-cooled slags. Granulated slags solidify to relatively small, uniform particles whereas air-cooled slags solidify in a large mass.

HIGHWAY USES AND PROCESSING REQUIREMENTS

Because they are produced in remote geographic locations, nonferrous slags are not commonly used in highway construction applications. Nonetheless, there have been reported uses of nonferrous slag as an aggregate substitute in hot mix asphalt and granular base applications.

Asphalt Concrete Aggregate

Phosphorus, copper, and nickel slags have been used as aggregate substitutes in hot mix paving. Air-cooled slags can be used as coarse or fine aggregate, while granulated slags can be used as fine aggregate.(1)

Granular Base, Embankment, and Fill

There has been limited use of copper, nickel, and phosphorus nonferrous slags as a granular base material. (See references 7,8,9,10 and 11.)

Nonferrous slags have the potential for use as an aggregate in embankments, although there is little documentation of use in this application. (See references 9,11,12,13, and 14.)

Processing of nonferrous air-cooled slags for use as aggregate involves conventional crushing and screening to meet the specified gradation requirements. Granulated slag particles are generally of fine aggregate size and may require blending with other suitable material to satisfy specified gradation requirements. Granulated copper and nickel slags can be expected to exhibit some cementitious properties similar to granulated phosphorus slags; however, there is no documented use of these slags in this (cementing) capacity.

MATERIAL PROPERTIES

Physical Properties

Table 11-1 lists some typical physical properties for nonferrous slags. Because they have similar properties, lead, lead-zinc, and zinc slags are grouped together.

Table 11-1. Typical physical properties of nonferrous slags.

Property	Nickel Slag	Copper Slag	Phosphorus Slag	Lead, Lead-Zinc, and Zinc Slags
Appearance	Reddish brown to brown-black, massive, angular, amorphous texture	Black, glassy, more vesicular when granulated	Black to dark gray, air-cooled is flat and elongated but granulated is uniform, angular	Black to red, glassy, sharp angular (cubical) particles
Unit weight, (kg/m^3)	3500(13)	2800 to 3800(15)	Air-cooled: 1360 to 1440 Expanded: 880 to 1000(16)	< 2500(17) to 3600(15)
Absorption (%)	0.37(13)	0.13(10)	1.0 to 1.5(18)	5.0(16)

Nickel Slag

Air-cooled nickel slag is brownish-black in color. It crushes to angular particles but has a smooth, glassy texture. The specific gravity of air-cooled nickel slag may be as high as 3.5(15), while the absorption is quite low (0.37 percent).(3) The unit weight of nickel slag is somewhat higher than that of conventional aggregate.

Granulated nickel slag is essentially an angular, black, glassy slag "sand" with most particles in the size range of minus 2 mm (No. 10 sieve) to plus 0.150 mm (No. 100 sieve).(15) It is more porous, with lower specific gravity and higher absorption, than air-cooled nickel slag.

Copper Slag

Air-cooled copper slag has a black color and glassy appearance. As a general rule, the specific gravity will vary with iron content, from a low of 2.8 to as high as 3.8.(15) The unit weight of copper slag is somewhat higher than that of conventional aggregate. The absorption of the material is typically very low (0.13 percent).(17)

Granulated copper slag is more porous and therefore has lower specific gravity and higher absorption than air-cooled copper slag. The granulated copper slag is made up of regularly shaped, angular particles, mostly between 4.75 mm (3/4 in) and 0.075 mm (No. 200 sieve) in size.

Phosphorus Slag

Air-cooled phosphorus slag tends to be black to dark gray, vitreous (glassy), and of irregular shape. Individual particles are generally flat and elongated, with sharp fracture faces similar to broken glass. The crushed material has a unit weight of 1360 to 1440 kg/m^3 (85 to 90 lb/ft),(13) which is less than that of conventional aggregate, with absorption values of about 1.0 to 1.5 percent.(10) Expanded phosphorus slag has a unit weight of 880 to 1000 kg/m^3 (55 to 62 lb/ft^3)(13) and has a higher absorption than air-cooled slag due to its more vesicular nature.

Granulated phosphorus slag is made up of regularly shaped, angular particles, mostly between 4.75 mm (1/4 inch) and 0.075 mm (No. 200 sieve) in size. It is more porous than air-cooled slag and consequently has lower specific gravity and higher absorption.

Lead, Lead-Zinc, and Zinc Slags

Slags of this group are often black to red in color and glassy. They have sharp, angular particles that are cubical in shape. The unit weights of lead, lead-zinc, and zinc slags are somewhat higher than conventional aggregate materials.

Granulated lead, lead-zinc, and zinc slags tend to be porous, with up to 5 percent absorption.(16) The specific gravity can vary from less than 2.5(16) to as high as 3.6.(15) These slags are made up of regularly shaped, angular particles, mostly between 4.75 mm (3/4 in) and 0.075 mm (No. 200 sieve) in size.

Chemical Properties

Copper, lead, lead-zinc, and zinc slags are essentially ferrous silicates, while phosphorus slag and nickel slag are primarily calcium/magnesium silicates. Table 11-2 lists typical chemical compositions of these slags.

Table 11-2. Typical chemical compositions of nonferrous slag, %.(14)

Element	Reverberatory Copper Slag	Nickel Slag	Phosphorus Slag	Lead Slag	Lead-Zinc Slag
SiO_2	36.6	29.0	41.3	35.0	17.6
Al_2O_3	8.1	trace	8.8	–	6.1
Fe_2O_3	–	53.06	–	–	–
CaO	2.0	3.96	44.1	22.2	19.5
MgO	–	1.56	–	–	1.3
FeO	35.3	–	–	28.7	–
K_2O	–	–	1.2	–	–
F	–	–	2.8	–	–
MnO	–	trace	–	–	2.0 - 3.0
P_2O_5	–	–	1.3	–	–
Cu	0.37	–	–	–	–
BaO	–	–	–	–	2.0
SO_3	–	0.36	–	–	–
Free CaO	–	–	–	–	–
S	0.7	–	–	1.1	2.8
PbO	–	–	–	–	0.8

During slag production, the sudden cooling that results in the vitrification of nonferrous slags (typically in the granulating process) prevents the molecules from being locked up in crystals. In the presence of an activator (such as calcium hydroxide from hydrating Portland cement) vitrified nonferrous slags react with water to form stable, cementitious, hydrated calcium silicates. The reactivity depends on the fineness to which the slag is ground (reactivity increases with fineness)(4) and the chemical composition of the slag and its glass content. These vitrified slags can be of such composition that when ground to proper fineness, they may also react directly with water to form hydration products that provide the slag with cementitious properties. A high iron content (essentially ferrous silicate slags) in these slags appears to limit hydraulicity and makes grinding difficult.

There is some evidence that nickel slag can be involved in the corrosion of iron and steel in the presence of moisture (probably galvanic corrosion). In Canada, where nickel slag is used in fill applications, it is common practice to provide a layer (typically 150 mm (6 in) thick) of natural aggregate between ferrous materials and the slag.(15)

Hydratable oxides may also be present in some nonferrous slags from some sources, which could potentially contribute to volumetric instability.

Depending on the ore and metallurgical process, nonferrous slags produced from sulfide ores can contain leachable elemental sulfur and heavy metals, which should be investigated prior to use. Sulfurous leachate is primarily of aesthetic concern, resulting in sulfur odor and possible discoloration of water in poor drainage conditions. In addition, phosphate rocks can contain between 30 and 200 ppm uranium. Most of this uranium is incorporated in the phosphorus slag and results in the release of some radiation (in the form of radon gas), although Tennessee Valley Authority tests have shown that the level of radiation does not appear to present a significant hazard.(19)

Mechanical Properties

Table 11-3 presents typical mechanical properties for nonferrous slags. Processed air-cooled and granulated copper, nickel, and phosphorus slags have a number of favorable mechanical

Table 11-3. Typical mechanical properties of nonferrous slags.

Test	Nickel Slag	Copper Slag	Phosphorus Slag	Lead, Lead-Zinc, and Zinc Slags
Los Angeles Abrasion Loss, %	22.1(17)	24.1(17)	< 30(10)	No data
Sodium Sulfate Soundness Loss, %	0.40(17)	0.90(17)	< 1(10)	No data
Angle of Internal Friction	~40°	40° - 53°(11)	No data	No data
Hardness (measured by Moh's scale of mineral hardness)	6 - 7(17)	6 - 7(17)	No data	No data

properties for aggregate use, including excellent soundness characteristics, good abrasion resistance, and good stability (high friction angle due to sharp, angular shape). However, nonferrous slags tend to be vitreous, or "glassy," which adversely affects their frictional properties (skid resistance), a potential problem if used in pavement surfaces.

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INTRODUCTION

A variety of nonferrous slags (air-cooled or granulated) including phosphorus, copper, nickel, and zinc slags, can be used as coarse and/or fine aggregate in hot mix asphalt pavements. Processed air-cooled and granulated copper, nickel, and phosphorus slags have a number of favorable mechanical properties for use as hot mix aggregate, including good soundness characteristics, abrasion resistance, and stability (high friction angle due to sharp, angular shape). However, some nonferrous slags are vitreous or "glassy," which can adversely affect their frictional resistance properties. Some glassy nonferrous slags may also be susceptible to moisture-related damage (stripping)

PERFORMANCE RECORD

Nonferrous slags tend to be produced in a few, generally remote geographic locations situated some distance from potential urban asphalt paving markets. As a result, nonferrous slags are not well-utilized.

Phosphorus Slag

Phosphorus slag aggregates have been used in dense graded hot mix surface course mixes for asphalt concrete pavements in Tennessee, particularly where high wet skid resistance was desired. Some use of air-cooled phosphorus slag aggregate in hot mix asphalt has also occurred in Montana (as fine aggregate) and in Tennessee and Florida. The use of phosphorus slag is addressed within conventional materials specifications in Tennessee and Florida for both coarse and fine hot mix asphalt aggregates.

Pavements incorporating phosphorus slag aggregate that have been properly selected, processed, and tested for specification compliance are reported to have demonstrated very satisfactory performance.(1) However, the use of unsuitable (glassy) phosphorus slag in open graded asphalt concrete pavements can result in inadequate frictional resistance properties.(1,2,3)

Copper Slag

There has been limited use of copper slag aggregates in hot mix asphalt pavements. Copper oxide blasting grit (fine copper slag) has reportedly been used in hot mix asphalt pavements in California, and granulated copper slag has reportedly been incorporated into asphalt mixes in Georgia to improve stability. Although it is rarely used, Michigan Department of Transportation specifications consider reverberatory copper slag to be a conventional coarse and fine aggregate for hot mix asphalt pavements.(4)

Nickel Slag

Very little documentation is available regarding the use of nickel slag in asphalt pavements in North America. Road trials in Ontario, Canada, incorporating air-cooled nickel slag in asphalt mixes are reported to have exhibited poor frictional resistance,(5) which was attributed to the glassy, smooth texture of the nickel slag aggregate. However, the more vesicular and porous granulated nickel slag produced in Japan has been successfully used as a skid resistant aggregate in surface course hot mix asphalt pavements.(6) Nickel slag aggregates are currently being used in hot mix paving asphalt mixes for the construction of highway pavements in the Dominican Republic.(7)

Zinc Slag

Although studies performed in Oklahoma for four types of zinc smelter wastes (fine slags) indicate that they are suitable for use as fine aggregate in hot mix asphalt concrete,(8) no North American documentation was identified regarding the use of zinc or lead slags in asphalt paving. A road trial completed in the United Kingdom using lead-zinc slag as the fine aggregate in asphalt concrete, in conjunction with limestone coarse aggregate, indicated good wearing properties but only moderate frictional resistance.(9)

MATERIAL PROCESSING REQUIREMENTS

Crushing and Screening

Air-cooled nonferrous slags to be used as aggregate in asphalt must be crushed and screened to the desired gradation (coarse or fine aggregate). This can be undertaken using conventional aggregate processing plant equipment.

Blending

Because granulated nonferrous slags tend to be uniform in size, they may require blending with other suitable materials to satisfy aggregate gradation requirements for asphalt mixtures.

ENGINEERING PROPERTIES

Some of the properties of nonferrous slags that are of particular interest when nonferrous slags are used as an aggregate in asphalt paving applications include particle shape and texture, gradation, unit weight, absorption, stability characteristics, wear resistance, frictional properties, adhesion, and resistance to freezing and thawing. Specific physical, chemical, and mineralogical properties of nonferrous slags depend in great part on the type of slag, method of production, type of furnace, and cooling procedures associated with their respective production processes. Consequently, each nonferrous slag aggregate must be considered by mineralogical type on a source-specific and cooling (air-cooled or granulated) basis.

Phosphorus Slag

Shape and Texture: Air-cooled phosphorus slag aggregates are black to dark gray in color and are generally flat and elongated. Individual particles tend to be vitreous (glassy) with sharp fracture faces similar to broken glass (irregular shape). Granulated phosphorus slag is made up of regularly shaped, angular particles.

Gradation: Air-cooled phosphorus slag can be processed into coarse or fine aggregate for hot mix asphalt to satisfy ASTM D692(10) and AASHTO M29(11) requirements. Granulated phosphorus slag can be used (after blending with other suitable material to satisfy AASHTO M29 gradation requirements) as a fine aggregate material.

Unit Weight: Crushed air-cooled phosphorus slag has a unit weight ranging from 1360 to 1440 kg/m^3 (85 to 90 lb/ft^3). Expanded phosphorus slag has unit weight of 880 to 1000 kg/m^3 (55 to 62 lb/ft^3).(12) Granulated phosphorus slag is more vesicular than air-cooled slag and consequently has lower unit weight.

Absorption: The absorption of air-cooled phosphorus slag is about 1.0 to 1.5 percent.(13) Both expanded and granulated phosphorus slags have higher absorption than air-cooled slag due to their more vesicular nature.

Stability Characteristics: No data on stability characteristics of phosphorus slag were identified, but processing and blending with other suitable material should be capable of yielding a stable material.

Wear Resistance: The high abrasion resistance of phosphorus slag can be expected to correspond to good wear resistance.

Frictional Properties: The favorable frictional resistance properties and abrasion resistance of crystalline, air-cooled phosphorus slag can be expected to contribute to good wet skid resistance in asphalt pavements.(1)

Adhesion: Good adhesion to asphalt cement is facilitated by the moderate absorption (1.0 to 1.5 percent) of air-cooled phosphorus slag aggregates.

Soundness: Phosphorus slags exhibit excellent soundness, which corresponds to good resistance to freeze-thaw exposure.(13)

Copper Slag

Shape and Texture: Air-cooled copper slag aggregates are black in color, and typically have a glassy appearance. Granulated copper slag aggregates are similar to air-cooled copper slag aggregates but more vesicular.

Gradation: Reverberatory copper slag can be processed into coarse or fine aggregate material for use in hot mix asphalt. It should be crushed and screened to produce aggregate that satisfies the gradation requirements for hot mix asphalt including ASTM D692(10) and AASHTO M29.(11) Granulated copper slag can be blended with other suitable material (to satisfy gradation requirements for AASHTO M29) as a fine aggregate for asphalt mixtures.

Unit Weight: Crushed air-cooled copper slag has a unit weight of 2800 to 3800 kg/m^3 (175 to 237 lb/ft^3).(14) The unit weight is somewhat higher than for conventional aggregates, resulting in increased density asphalt concrete (lower yield). Granulated copper slag is more vesicular and therefore has a lower unit weight than air-cooled slag.

Absorption: Air-cooled copper slag absorption is typically very low (0.13 percent).(15) Granulated copper slag has a higher absorption than air-cooled slag.

Stability Characteristics: The high angularity and friction angle (up to 53 °)(16) of copper slag aggregates contribute to excellent stability and load bearing capacity. In Georgia, granulated slag is reportedly added to hot mix asphalt mixes in conjunction with limestone aggregate to increase stability and reduce Marshall flow.(17)

Wear Resistance: The superior hardness and abrasion resistance of copper slag aggregates compared with most conventional aggregates contribute to good wear resistance.(8,15)

Frictional Properties: No specific data were identified.

Adhesion: No specific data were identified, but low absorption values and the glassy nature of copper slag suggest that stripping might be a concern.

Soundness: The excellent soundness exhibited by copper slag aggregate reflects good resistance to freeze-thaw exposure.(15)

Nickel Slag

Shape and Texture: Air-cooled nickel slag aggregates are reddish brown to brown-black in color. It can be crushed to angular particles but has a massive, angular, smooth, amorphous texture. Granulated nickel slag is essentially an angular, black, glassy slag "sand."

Gradation: No specific data were identified, but no problems are anticipated in producing the appropriate gradation.

Unit Weight: The unit weight of crushed air-cooled nickel slag tends to be as high as 3500 kg/m^3 (219 lb/ft^3).(18) Granulated nickel slag is more vesicular and has a lower unit weight than air-cooled nickel slag.

Absorption: Air-cooled nickel slag has quite low absorption (0.37 percent).(18) Granulated nickel slag is more vesicular, and has higher absorption than air-cooled nickel slag.

Stability Characteristics: The high angularity and friction angle (approximately 40°)(16) of nickel slag aggregates contribute to excellent stability and load bearing capacity.

Wear Resistance: No data were identified, but the high hardness and good soundness properties suggest favorable wear resistance.

Frictional Properties: No data were identified, but the high angularity and potential wear resistance could be expected to result in favorable frictional properties.

Adhesion: No specific data were identified.

Soundness: Nickel slag aggregates display very good soundness (resisting freeze-thaw deterioration), are harder than conventional granular aggregates and have good resistance to wear.(8)

Lead, Lead-Zinc and Zinc Slags

Shape and Texture: Lead, lead-zinc, and zinc slags are black to red in color and have glassy, sharp, angular (cubical) particles.

Gradation: No specific data were identified.

Unit Weight: The unit weight of granulated lead, lead-zinc, and zinc slags can vary from less than 2500 kg/m^3 to as high as 3600 kg/m^3 (156 to 225 lb/ft^3).(8,14)

Absorption: Granulated lead, lead-zinc, and zinc slags tend to be porous, with absorptions up to about 5 percent.(12)

Stability Characteristics: Although no specific data were identified, it is anticipated that these slags would produce acceptable stability characteristics.

Wear Resistance: Although no specific data were identified, it is anticipated that these slags would produce acceptable wear resistance characteristics.

Frictional Properties: Although no specific data were identified, it is anticipated that these slags would produce acceptable frictional properties.

Adhesion: Although no specific data were identified, it is anticipated that these slags would produce acceptable adhesion characteristics.

Soundness: Although no specific data were identified, it is anticipated that these slags would exhibit adequate soundness properties.

DESIGN CONSIDERATIONS

Mix Design

Conventional asphalt mix design methods (e.g., Marshall, Hveem, SHRP) are applicable for the design of hot mix asphalt containing nonferrous slag (particularly air-cooled phosphorus and reverberatory copper slag) aggregates. No special procedures are required for aggregate gradations. Both coarse and fine nonferrous slag aggregates can be incorporated in hot mix asphalt, provided that the physical requirements of ASTM D692(10) and/or AASHTO M29(11) are satisfied. No special provisions are required for nonferrous slag, and conventional hot mix gradations specifications may be used. Blending with other suitable hot mix asphalt aggregates may be necessary to achieve gradation specifications compliance. Due to the difference in unit weights, mix designs are usually calculated on a volumetric basis.

Some glassy nonferrous slags may be susceptible to moisture-related damage (stripping) and therefore, the mix design should include a stripping resistance or retained stability test (AASHTO T283(19) and MTO LS-283(20)) and the addition of hydrated lime or other anti-stripping agents may be warranted. Due to their glassy nature, some air-cooled nonferrous slags may exhibit poor frictional properties.

Structural Design

Conventional AASHTO pavement structure design methods are appropriate for asphalt paving incorporating nonferrous slag aggregates.

CONSTRUCTION PROCEDURES

Mixing

The same production methods and equipment used for conventional hot mix asphalt can be used for production of hot mix asphalt containing nonferrous slag.

Placing and Compaction

The same equipment and construction procedures used for conventional hot mix asphalt aggregate can be used for hot mix asphalt paving mixtures incorporating nonferrous slag aggregates.

Quality Control

Standard and field and laboratory tests for compacted bituminous mixes are given by AASHTO T168,(21) T166,(22) and ASTM D2950.(23) ASTM D4792(24) should be considered for nonferrous slags where significant quantities of hydratable oxides may be present.

UNRESOLVED ISSUES

There is a need to investigate the poor frictional resistance properties associated with the use of air-cooled nickel slag and lead-zinc, slags which limit their use as aggregates in asphalt pavements. Particular attention is required to avoid using glassy aggregates as they impart poor frictional resistance properties to asphalt concrete pavements.

Also, there is a need to investigate the potential use of nonferrous slag in surface treatments and cold mixes. Very little documentation data are available regarding their use in this application.

There is also little documentation regarding the engineering properties and performance/serviceability of lead, lead-zinc, and zinc slags.

Finally, environmental research, including chemical and leaching analyses and environmental assessments, is required to evaluate potential environmental issues associated with the use of these slag materials in asphalt paving applications.

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INTRODUCTION

The use of copper, nickel and phosphorus slag aggregates as granular base has occurred primarily in rural areas close to the remote locations where these slags are produced. No North American use of lead or zinc slags as granular base has been confirmed. The unit weights of copper and nickel slags tend to be greater than those of conventional aggregates, with a corresponding lower yield and increased transportation and placement costs. The lower unit weight of phosphorus slag aggregates compared to conventional aggregates results in somewhat higher yield (greater volume for the same weight).

PERFORMANCE RECORD

Copper and nickel slags have been used for many years as granular base in mining roads,(1) where they have demonstrated satisfactory performance in what are generally considered to be very severe traffic and operating conditions. In Michigan, reverberatory copper slag is considered to be a conventional aggregate and is covered by state specifications for granular base. Similarly, nickel slag is considered a conventional granular aggregate in Ontario, Canada, and is used extensively as road base in areas near where it is produced. Phosphorus slag has also been used in large quantities in Montana for aggregate in base courses.(2)

Some of the desirable features of copper, nickel and phosphorus slags in granular base applications include high stability and good drainage characteristics (3,4) as well as good resistance to freeze-thaw exposure and mechanical degradation.(4,5,6)

While limited toxicity testing data indicate that the leachates from specific copper and phosphorus slags are not hazardous(3,7) (as measured by USEPA hazardous waste testing methods), nonferrous slags produced from sulfide ores may contain leachable sulfur. If placed in poor drainage conditions and in extended contact with stagnant or slow moving water, sulfur odor and water discoloration may result. Due to concerns regarding the leachability of heavy metals, most lead, lead-zinc and zinc slags are generally considered to be unsuitable for use in granular base. However, there has reportedly been use of specially processed lead and zinc slag aggregates as bulk fill in land reclamations in Japan and in granular base for floor slabs in buildings in the United Kingdom.(8)

MATERIAL PROCESSING REQUIREMENTS

Crushing and Screening

Copper, nickel and phosphorus slags must be crushed and screened to produce a granular base aggregate. This can readily be accomplished using conventional crushing and screening equipment.

Blending

Crushing of air-cooled nickel slag produces a low quantity of finer particles, and consequently blending with additional crushed fine material may be necessary to satisfy gradation requirements.(1,5) Other nonferrous slag aggregates may also require blending with conventional granular aggregates to optimize aggregate properties. Crushed fines, having high angularity, should be used (rather than natural sand) to "lock-up" the smooth, hard nickel slag aggregates.

ENGINEERING PROPERTIES

Some of the engineering properties of nonferrous slag aggregates that are of particular interest when nonferrous slags are used in granular base applications include gradation, specific gravity, durability, stability, and drainage characteristics.

Copper Slag Aggregates

<u>Gradation</u>: Copper slags can be crushed and screened to satisfy the AASHTO M147(9) gradation requirements for granular aggregates.

<u>Specific Gravity</u>: With specific gravities ranging from 2.8 to 3.8, copper slag aggregates are decidedly heavier than conventional granular material.(1)

<u>Durability</u>: Copper slag aggregates display very good soundness (resisting freeze-thaw deterioration), are harder than conventional granular aggregates and have good resistance to wear.

<u>Stability</u>: The high angularity and friction angle (up to 53°) of copper slag aggregates contribute to excellent stability and load bearing capacity.(3)

<u>Drainage Characteristics</u>: Copper slag aggregates tend to be free draining and are not frost susceptible.(3)

Nickel Slag Aggregates

Gradation: Nickel slags can be crushed and screened to satisfy the AASHTO M147(9) gradation requirements for granular aggregates.

Specific Gravity: Like copper slag, nickel slag aggregates are substantially heavier than conventional granular aggregates (specific gravity to 3.5).(1)

Durability: Nickel slag aggregates exhibit higher soundness, hardness and abrasion resistance properties than conventional aggregates.(4)

Stability: Nickel slag granular base aggregates exhibit good stability and high bearing capacity due to their angular shape and high angle of internal friction.(5)

Drainage Characteristics: Nickel slag aggregates are free draining and non-frost susceptible.

Phosphorus Slag Aggregates

Gradation: Phosphorus slags can be crushed and screened to satisfy the AASHTO M147(9) gradation requirements for granular aggregates.

Specific Gravity: Crushed air-cooled phosphorus slag aggregates are somewhat lighter than conventional granular aggregates.(10)

Durability: Phosphorus slag aggregates exhibit very good soundness (high resistance to freeze-thaw deterioration) and good resistance to mechanical degradation.(6)

Stability: Due to their sharp, angular shape, phosphorus slag aggregates demonstrate good stability.

Drainage Characteristics: Phosphorus slag aggregates have good drainage characteristics.

DESIGN CONSIDERATIONS

Properly processed copper, nickel and phosphorus slag aggregates can readily satisfy the gradation and physical requirements of AASHTO M147(9) and ASTM D2940.(11)

The high stability of properly graded, crushed, nonferrous slag aggregates provides good load transfer to a weaker subgrade. Due to the low fines generated by crushing nickel slags, it is often necessary to supplement nickel slag aggregates with suitable fine aggregate material.

Standard AASHTO pavement structural design procedures can be employed for granular base containing nonferrous slag aggregates. The appropriate structural number for nonferrous slag aggregates should be established by resilient modulus testing.

CONSTRUCTION PROCEDURES

Material Handling and Storage

The same equipment and procedures used to stockpile and handle conventional aggregates can be used for nonferrous slag aggregates.

Due to their high angularity, greater care should be taken when stockpiling and handling nonferrous aggregates to avoid segregation. Precautions may be required to ensure that nonferrous slag aggregate stockpiles are sufficiently separated from watercourses to prevent leachate contamination.

Mixing, Placing and Compacting

Nonferrous slag aggregates can be difficult to compact and may require additional effort (for instance, vibratory rollers) to achieve adequate compaction.(4,5)

Quality Control

The same test procedures used for conventional aggregate are appropriate for granular base applications when using nonferrous slag. Standard laboratory and field tests for compacted density and field measurement of compaction are given by AASHTO test methods T191,(12) T205,(13) T238(14) and T239.(15)

UNRESOLVED ISSUES

The most pressing issue that needs to be resolved is the environmental suitability of nonferrous slags for granular base applications. Materials from each source must be assessed for heavy metals content and leachability. Phosphorus slag radioactivity concerns should also be investigated.

Further, there is a need to establish standard methods and clear guidelines to assess the suitability of nonferrous slags that may be in contact with groundwater or watercourses.

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INTRODUCTION

Although there is little documented use of nonferrous slags as aggregate in embankments or fill, both air-cooled and granulated nonferrous slags are potentially useful for these applications. Nonferrous slag that is suitable for use as a granular base (copper, nickel, and phosphorus slags) will generally exceed specifications for embankment and fill construction. The high stability of nonferrous slag aggregates can be used advantageously to provide good load transfer to weaker subgrades.

PERFORMANCE RECORD

Some of the desirable features of nonferrous slags for embankment construction include their high stability, good drainage characteristics, and negligible plasticity. Slags from the production of copper, nickel, lead and zinc have higher unit weight, resulting in lower yield and potentially increased long-term settlement if placed over compressible soils.

While limited toxicity testing data indicate that the leachate from specific copper and phosphorus slags are not hazardous(1,2) (as measured by USEPA hazardous waste testing procedures), nonferrous slags produced from sulfide ores may contain leachable sulfur. If placed in poor drainage conditions and in extended contact with stagnant or slow-moving water, sulfur odor and water discoloration may result.

Copper Slag

Copper slag (air-cooled and granulated) suitable for use as granular road base material has suitable engineering properties for use in embankments or fill applications.(3) Reverberatory copper slag (copper slag derived from reverberatory furnaces used for the smelting of copper concentrates)(4,5) is covered by conventional specifications for granular aggregate in Michigan.

Nickel Slag

Nickel slag (air-cooled and granulated) suitable for use as granular road base material has suitable engineering properties for use in embankment or fill applications.(6) Nickel slag is considered as a conventional granular aggregate and railway ballast in Ontario, Canada.

Due to galvanic corrosion concerns, steel pipelines, services and piles should be separated from nickel slag (for instance, using a 150 mm (6 in) thick layer of natural aggregate material).

Phosphorus Slag

Phosphorus slag has suitable engineering properties for use in embankment or fill applications, and large quantities of phosphorus slag have been used in Montana for aggregate in base courses.(6) The low unit weight of phosphorus slag aggregates results in higher yield (greater volume for the same weight), reduced dead load (leading to reduced long-term settlement of compressible soils), and reduced lateral pressures compared with conventional fill materials.

Lead, Lead-Zinc, and Zinc Slag

Although no documentation was found regarding the use of lead or zinc slags in embankments or fill in North America, these slags are considered to have suitable engineering properties for such use.(5) Lead-zinc slag from production of lead and zinc using the proprietary Imperial Smelting Process (ISP) has been used in Japan as fill in land reclamations and in the United Kingdom as granular base below grade for large buildings.(7)

MATERIAL PROCESSING REQUIREMENTS

Crushing and Screening

Other than crushing of large, air-cooled pieces, nonferrous slags require minimal processing to satisfy the physical requirements for use in embankments or fill.

Blending

If necessary, the nonferrous slag aggregates can be blended with conventional embankment or fill materials (rock, soil, aggregates) to meet required gradation specifications.

ENGINEERING PROPERTIES

Some of the engineering properties of nonferrous slags that are of particular interest when nonferrous slags are used in embankment or fill applications include gradation, unit weight, absorption, soundness, stability, drainage, and corrosivity.

Copper Slag

Gradation: Reverberatory copper slag can be processed into coarse or fine aggregate material for use in embankment applications. Copper slag can readily satisfy the gradation and physical requirements of AASHTO M145.(11)

Unit Weight: Copper slag has a unit weight of 2800 to 3800 kg/m^3 (175 to 237 lb/ft^3).(8) The unit weight is somewhat higher than for conventional aggregates, resulting in increased density asphalt concrete (lower yield).

Absorption: Air-cooled copper slag absorption is typically very low (0.13 percent).(9) Granulated copper slag has a higher absorption than air-cooled slag.

Soundness: The excellent soundness exhibited by copper slag aggregate reflects good resistance to freeze-thaw exposure.(15)

Stability: The high angularity and friction angle (up to 53 °)(3) of copper slag aggregates contribute to excellent stability and load bearing capacity.

Drainage Characteristics: Copper slag aggregates are free draining and are not frost susceptible.(3)

Corrosivity: No data were identified to permit an evaluation of the potential corrosivity of copper slag.

Nickel Slag

Gradation: No specific data were identified for this application; however, no problems are anticipated in meeting the appropriate gradation requirements.

Unit Weight: The unit weight of crushed air-cooled nickel slag tends to be as high as 3500 kg/m^3 (219 lb/ft^3).(5) Granulated nickel slag is more vesicular, and has lower unit weight than air-cooled nickel slag.

Absorption: Air-cooled nickel slag has quite low absorption (0.37 percent).(5) Granulated nickel slag is more vesicular and has higher absorption than air-cooled nickel slag.

Soundness: Nickel slag aggregates display very good soundness (resisting freeze-thaw deterioration), are harder than conventional granular aggregates, and have good resistance to wear.(10)

Stability: The high angularity and friction angle (approximately 40°)(3) of nickel slag aggregates contribute to excellent stability and load bearing capacity.

Drainage Characteristics: Nickel slag aggregates are free draining and are not frost susceptible.(3)

Corrosivity: There is some evidence that nickel slag can contribute to the corrosion of ferrous metals in the presence of moisture, probably due to galvanic effects (differences in electrochemical potential between the nickel slag and iron or steel).

Phosphorus Slag

Gradation: Air-cooled phosphorus slag can readily satisfy the AASHTO M145(11) gradation and physical requirements for embankment aggregates.

Unit Weight: The unit weight of crushed air-cooled phosphorus slag ranges from 1360 to 1440 kg/m^3 (85 to 90 lb/ft^3). The unit weight of expanded phosphorus slag is about 880 to 1000 kg/m^3 (55 to 62 lb/ft^3).(12) Granulated phosphorus slag is more vesicular than air-cooled slag and consequently has lower unit weight.

Absorption: The absorption of air-cooled phosphorus slag is about 1.0 to 1.5 percent.(13) Both expanded and granulated phosphorus slags have higher absorption than air-cooled slag due to their more vesicular nature.

Soundness: Phosphorus slags exhibit excellent soundness, which corresponds to good resistance to freeze-thaw exposure.(13)

Stability: No data were available regarding the stability characteristics of phosphorus slag; however, a properly graded material should be capable of yielding a stable fill.

Drainage Characteristics: Phosphorus slag aggregates are generally nonplastic, free draining, and not frost susceptible.(3)

Corrosivity: No data were identified to permit an assessment of the potential corrosivity of phosphorus slag

DESIGN CONSIDERATIONS

Structural design procedures employed for embankments containing nonferrous slag are the same as design procedures for conventional embankment materials.

There are no standard specifications covering nonferrous slag use as embankment or fill. The designer may be required to satisfy moisture content criteria according to AASHTO T99(14) and to implement appropriate material handling practices to avoid segregation and breakage.

CONSTRUCTION PROCEDURES

Material Handling and Storage

The same methods and equipment used to store or stockpile conventional aggregates are applicable for nonferrous slag.

Precautions may be required to ensure that stockpiles containing nonferrous slag materials are sufficiently separated from watercourses to prevent leachate contamination. The material should be placed in a manner that allows free drainage and prevents ponding within or against the material.

Placing and Compacting

Due to their high angularity, additional effort (for instance, using vibratory rollers) may be required to compact copper, nickel, and phosphorus slags to their maximum densities.

Quality Control

The same test procedures used for conventional aggregate are appropriate for nonferrous slags. Standard laboratory and field tests for compacted density and field measurement of compaction are given by AASHTO T191,(15) T205,(16) T238,(17) and T239.(18)

UNRESOLVED ISSUES

The main unresolved issue pertaining to the use of nonferrous slags in embankments or fill is that of environmental suitability. The material for each application must be assessed for leachate toxicity. Phosphorus slag must also be assessed for potential radioactivity.

Further, standard methods and clear guidelines to assess the suitability of nonferrous slags that may be in contact with groundwater or watercourses should be established. The potential corrosion risk to buried utilities within nickel as well as other nonferrous slag fills should be evaluated.

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ORIGIN

Processing of crushed stone for use as construction aggregate consists of blasting, primary and secondary crushing, washing, screening, and stockpiling operations.(1) Quarry by-products are produced during crushing and washing operations. There are three types of quarry by-products resulting from these operations: screenings, pond fines, and baghouse fines.

Screenings

Screenings is a generic term used to designate the finer fraction of crushed stone that accumulates after primary and secondary crushing and separation on a 4.75 mm (No. 4) sieve. The size distribution, particle shape, and other physical properties can be somewhat different from one quarry location to another, depending on the geological source of the rock quarried, the crushing equipment used, and the method used for coarse aggregate separation. Screenings generally contain freshly fractured faces, have a fairly uniform gradation, and do not usually contain large quantities of plastic fines.(2)

Settling Pond Fines

Pond fines refer to the fines obtained from the washing of a crushed stone aggregate. During production, the coarser size range (greater than No. 30 sieve) from washing may be recovered by means of a sand screw classifier. The remainder of the fines in the overflow are discharged to a series of sequential settling ponds or basins, where they settle by gravity, sometimes with the help of flocculating polymers. Pond clay is a term usually used to describe waste fines derived from the washing of natural sands and gravels.(3)

Baghouse Fines

Some quarries operate as dry plants because of dry climatic conditions or a lack of market for washed aggregate products. Dry plant operation requires the use of dust collection systems, such as cyclones and baghouses, to capture dusts generated during crushing operations. These dusts are referred to as baghouse fines.

It is estimated that at least 159 million metric tons (175 million tons) of quarry by-products are being generated each year, mostly from crushed stone production operations. As much as 3.6 billion metric tons (4 billion tons) of quarry by-products have probably accumulated.(3)

CURRENT MANAGEMENT OPTIONS

Recycling

The exact quantity of quarry by-products that are being recycled is not known. Very little of the 159 million metric tons (175 million ton) produced annually is thought to be used, especially the pond fines. In a recent survey, three states (Arizona, Illinois, and Missouri) indicated that quarry by-products have been used as an embankment material and three other states (Florida, Georgia, and Vermont) indicated some use of quarry by-products in base or subbase applications.(4) Some use has been made of limestone screenings as agricultural limestone, and baghouse fines from quarry sources have been used as mineral filler in asphalt paving.

Disposal

Virtually all of the quarry by-products generated are disposed of at the quarry source. Screenings are stockpiled in a dry or damp form. Pond fines are conveyed in slurry form to settling ponds. Baghouse fines are usually sluiced into settling ponds.

MARKET SOURCES

Quarry by-products are available at over 3,000 stone quarry operations located in every state except Delaware. Screenings are readily available at most quarries, especially limestone quarries. Although large quantities of pond fines are produced, they must be reclaimed from the ponds and adequately dewatered before they can be considered suitable for use. Baghouse fines are only produced at dry processing plants in areas where there is a lack of market for washed aggregate products. These areas are usually in the more arid regions of the country in the western states.

Screenings

At most quarries, screenings are stockpiled separately at or near the primary or secondary crushing equipment. Screenings are essentially a damp, silty, sand-sized material, usually with an estimated 5 to 10 percent moisture content, depending on the length of time the screenings have been stockpiled. The material is easily recovered by using standard excavation equipment and dump vehicles for loading and hauling.

Pond Fines

Pond fines are usually cleaned or removed from settling ponds by draglines, stockpiled for several months to allow for natural dewatering, then truck hauled, usually to another location on the quarry site. Larger production operations may use equipment such as hydrocyclones, clarifiers, thickeners, or belt presses for dewatering the fines. When dredged from settling ponds, the moisture contents of the fines can be as high as 70 to 80 percent. Final moisture contents in the 20 to 30 percent range are attainable, with the degree of dewatering dependent on the mineralogy and gradation of the fines, equipment used, as well as climatic conditions. Unless sufficiently dewatered, pond fines are too wet to be considered a useable material. The physical and chemical properties of settling pond fines can vary widely with aggregate type and source, but are relatively consistent within a single quarry.(3)

Baghouse Fines

The properties of baghouse fines vary with rock type, processing equipment, dust collection equipment, and point of collection within the plant. Baghouse fines, because they are generated as a fine, dry powder, are usually less of a handling problem than either the screenings or the pond fines. For a given aggregate and production source, the physical and chemical properties tend to be relatively uniform over time.(5)

HIGHWAY USES AND PROCESSING REQUIREMENTS

Portland Cement Concrete, Asphalt Concrete, and Flowable Fill Aggregate

Screenings have properties that are suitable for use as an aggregate substitute in Portland cement concrete, flowable fill, and asphalt paving applications. Baghouse fines and/or pond fines could potentially replace much of the fines in flowable fill mixes, depending on strength requirements, which are usually fairly low.

Granular Base

If properly blended, screenings can potentially be used in granular base courses.

Mineral Filler

Quarry baghouse fines have been successfully used as a mineral filler in asphalt paving. Dewatered pond fines have the potential for use as a mineral filler in hot mix asphalt paving, depending on the clay content of the pond fines.

The only quarry fines by-product that would require significant processing for any of the foregoing applications are the pond fines, which would have to be adequately dewatered before use. Pond fines would require a greater degree of dewatering for use as mineral filler in asphalt than for use in flowable fill.

MATERIAL PROPERTIES

Physical Properties

Screenings

Screenings are a uniformly sized, fine, sandy material with some silt particles. Screenings commonly range in particle size from 3.2 mm (1/8 in) down to finer than 0.075 mm (No. 200 sieve). Normally, the percentage of particle sizes finer than 0.075 mm (No. 200 sieve) is 10 percent or less by weight. Stockpiles of screenings may contain some particles up to 4.75 mm (No. 4 sieve) in size, which is usually the screen size used for separation. Some weathered rock or overburden material may be present in the screenings from certain processing operations.

Table 12-1 compares the particle size distribution of the fines fraction (finer than No. 4 sieve) of screenings from several different aggregate sources. Different types of crushers were used to produce these screenings. Despite differences in rock types and crushing machinery, the gradings of the resultant screenings are quite similar.

Table 12-1. Average particle size distribution of screenings from processing of different quarry sources.(3)

Sieve Size	Quarry Source					
	Flint	Trachyte	Limestone	Diabase	Granite	Quartzite
	Percent Passing					
3.18 mm (1/8 in)	100	100	100	100	100	100
2.36 mm (No. 8)	83	82	85	87	86	88
1.18 mm (No. 16)	51	52	54	61	60	71
0.600 mm (No. 30)	31	33	34	41	42	57
0.300 mm (No. 50)	18	22	23	27	28	33
0.150 mm (No. 100)	10	13	15	17	19	15
0.075 mm (No. 200)	6	8	7	9	12	7

Pond Fines

Pond fines, when initially recovered from the pond, consist of a low solids content, fine-grained slurry, usually with 90 to 95 percent of the particles finer than 0.15 mm (No. 100 sieve) and 80 percent or more of the particles finer than 0.075 mm (No. 200 sieve).

Table 12-2 compares the average particle size distribution of pond fines sampled from two quarries using two different dewatering processes (a sand screw and a U.S. Bureau of Mines dewatering unit). Table 12-2 also includes a listing of gradation ranges for each of the pond fines samples. The table records particle sizing from 0.6 mm (No. 30 sieve) down to the 0.045 mm (No. 325 sieve) size. Within this size range, the grading of the samples is fairly consistent.

Table 12-2. Particle size distribution of pond fines from dewatering systems at dolomitic limestone and diabase quarries (percent passing). (3)

Particle Size	Dolomitic Limestone Plant				Diabase Plant			
	Sand Screw		USBM Fines		Sand Screw		USBM Fines	
	Average	Range	Average	Range	Average	Range	Average	Range
0.600 mm (No. 30 sieve)	99.9	99.2-100	99.9	99.9-100	100	99.9-100	99.9	97.2-100
0.300 mm (No. 50 sieve)	99.1	97.7-99.9	99.8	99.3-99.9	99.8	99.1-100	99.3	90.2-100
0.15 mm (No. 100 sieve)	94.9	92.6-98.1	98.3	97.2-99.6	95.1	90.3-97.9	94.8	77.6-98.6
.075 mm (No. 200 sieve)	80.4	70.8-89.1	89.9	86.4-94.6	75.2	65.0-83.6	78.3	56.8-91.8
.045 mm (No. 325 sieve)	61.8	47.1-75.9	76.1	73.0-83.5	60.1	99.3-68.6	65	42.6-81.9

Baghouse Fines

Although particle sizing may vary somewhat with fines from different types of stone, the range in particle size is from 0.075 mm (No. 200 sieve) down to 0.001 mm or even finer.

Table 12-3 compares the particle size distribution of 10 different samples of quarry baghouse fines from the processing of four different types of stone. All are predominantly finer than 0.05 mm (No. 270 sieve) and most have a substantial percentage of particles finer than 0.01 mm, although there is some variation in the finer sizes.(5)

Chemical Properties

There is very little difference in the chemistry or mineralogy of screenings and pond fines from the same quarry or rock source, and also very little difference in the chemistry within the

Table 12-3. Particle size distribution of baghouse dusts from processing of several different rock types.[3]

Rock Type	Percent Passing Sieve Size							
	.075 mm (No. 200)	.05 mm (No. 270)	.03 mm	.02 mm	.01 mm	.005 mm	.003 mm	.001 mm
Limestone	100	96	82	67	43	23	14	4
Granite	100	98	95	84	53	29	17	7
Granite	100	89	43	18	8	3	2	1
Granite	100	94	69	51	32	16	10	4
Granite	100	100	99	96	78	49	32	12
Trap Rock	100	98	89	76	48	24	14	5
Limestone	100	96	93	89	74	46	31	12
Limestone	100	95	66	37	11	7	5	3
Limestone	100	95	80	62	43	27	18	7
Quartz	100	100	100	100	99	93	75	10

size fractions of the pond fines.[5] Table 12-4 provides a listing of the chemical and mineralogical constituents of screenings (minus 4.75 mm (No. 4 sieve) material), and pond fines from the same granite quarry. The pond fine components are further subdivided into the overall bulk sample and the portions of the sample that are both coarser and finer than 0.106 mm (No. 140 sieve).

Mechanical Properties

Published data on the mechanical properties (unit weight, compacted density, California Bearing Ratio (CBR), shear strength, etc.) of either screenings, settling pond fines, or baghouse fines are not readily available. The mechanical properties of quarry by-products can be expected to vary according to the type of rock from which the by-products were derived.

Table 12-4. Chemical composition and mineralogical identity of screenings and pond fines from a granite quarry.(3)

Chemical Composition				
Constituent	Screenings	Pond Fines		
		Bulk	Plus .106 mm (No. 140 sieve)	Minus .106 mm (No. 140 sieve)
SiO_2	75.25	74.98	77.44	73.37
Al_2O_3	13.63	13.31	12.43	14.16
K_2O	5.34	5.01	4.57	5.30
Na_2O	3.00	2.81	2.49	3.02
CaO	1.28	2.07	1.00	2.77
Fe_2O_3	1.22	1.28	1.28	1.27
MgO	0.33	0.44	0.40	0.47
MnO	0.07	0.03	0.03	0.04
Mineralogic Identity				
Constituent	**Screenings**	**Pond Fines**		
		Bulk	**Plus .106 mm (No. 140 sieve)**	**Minus .106 mm (No. 140 sieve)**
Quartz	23.0	25.1	31.5	20.9
K-Feldspar	35.0	33.7	27.1	38.0
Plagioclase	39.2	35.7	31.1	38.7
Muscovite	1.4	3.7	8.7	0.0
Biotite	1.4	0.9	1.6	0.4
Diopside	0.0	1.2	0.0	2.0

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INTRODUCTION

Quarry by-products (screenings, pond fines, or baghouse fines) can be used as a filler aggregate or as a partial, or possibly a complete, replacement for the pozzolan component in flowable fill mixes. Screenings can be substituted for sand (or other granular filler materials) and may comprise up to as high as 85 percent by dry weight of such mixes. Pond fines or baghouse fines may be used for some, or possibly even all, of the aggregate content and may comprise up to as high as 95 percent by dry weight of flowable fill mixes.(1)

PERFORMANCE RECORD

There are no known commercial applications to date that have made use of quarry by-products in flowable fill applications. However, a report prepared for the National Stone Association identifies flowable fill as a promising application for quarry by-products.(2)

Most flowable fill applications are designed for comparatively low in-place compressive strength development (from 340 to 1400 kPa (50 to 200 lb/in^2)). The use of quarry by-products (screenings, pond fines, or baghouse fines) to replace some or all of the sand filler or fines is not considered detrimental to the strength development of the flowable fill.

MATERIAL PROCESSING REQUIREMENTS

Screening

It is unlikely that the use of crushed stone screenings as a filler in flowable fill mixes would require any processing since the screenings are produced dry or slightly moist and are generally stockpiled in the same manner as crushed stone or sand and gravel. Minimal sizing on a vibratory screen may be needed if there are any oversize (plus 19 mm (3/4 in)) particles in the screenings. If screenings are stockpiled during a rainy period, some drying may also be necessary.

Dewatering

The use of pond fines as a filler in flowable fill will require some type of dewatering once the fines have been reclaimed from a settling pond. The pond fines may be stockpiled for natural dewatering or passed through a mechanical dewatering device (such as a hydroclone or belt press) to reduce the moisture content.

ENGINEERING PROPERTIES

Some of the engineering properties of quarry by-products that are of particular importance when quarry fines are used in flowable fill mixtures are gradation, moisture content, and unit weight.

Gradation: Gradation is important from the perspective of comparing the gradation of commonly used flowable fill materials (such as fly ash and sand) with potential replacement products.

Screenings are nearly all finer than 3.2 mm (1/8 in) and have low percentages (6 to 12 percent) below a 0.075 mm (No. 200 sieve) sieve size. This indicates that screenings are basically well-graded, medium to fine sand-sized materials with a small amount of silt-sized particles.

Recovered pond fines can be expected to have a size range from 100 percent passing 0.59 mm (No. 30 sieve) down to between an average of 75 to 90 percent passing 0.075 mm (No. 200 sieve). This is essentially the same size range as coal fly ash (a common additive in flowable fill mixes), which is a predominantly silt-sized material. Baghouse fines are all finer than 0.075 mm (No. 200 sieve) and nearly all particles are also finer than 0.045 mm (No. 325 sieve). Baghouse fines are nonplastic and similar in sizing and consistency to a finely sized fly ash.

Moisture Content: Screenings, because they are stockpiled in the open, can have a fairly wide range of moisture content within the same stockpile or from one quarry location to another. Pond fines, when reclaimed, may have moisture contents as high as 70 to 80 percent, and must be dewatered, either by stockpiling or by processing. Baghouse fines are available as a dry powder.

Unit Weight: The unit weight of quarry by-products can vary according to the type of rock processed, but is expected to be within the same range as the rock source from which it was derived. Screenings will normally have a higher unit weight than pond fines, with baghouse fines probably being slightly lower in unit weight than pond fines.

Some of the flowable fill mix characteristics of interest include mix strength, flowability, time of hardening, and bleeding and shrinkage.

Mix Strength: Strength development in flowable fill mixes should not be affected to any great extent by the use of quarry by-products. In mixes with high fly ash content, ultimate strengths in excess of 1035 kPa (150 lb/in^2) may require jack hammers if removal is necessary.(3) Use of pond fines or baghouse fines in lieu of some of the fly ash should help to maintain the strength development below this value because the pond fines or baghouse fines are not pozzolanic.

On the other hand, if additional strength is required, screenings used in place of all, or a portion of, natural sand should not be detrimental to strength development since quarry screenings are a manufactured sand from the crushing of rock. The particles are mostly angular with good interlocking characteristics and a relatively high angle of internal friction, similar to or possibly even higher than that of natural sand.

Flowability: The use of quarry fines may have an effect on the flowability of a flowable fill mix, depending on the type and amount of quarry fines that are used. The use of pond fines, or baghouse fines, in place of a portion of the mix may cause the mix to be somewhat less flowable at the same moisture content, because of the angularity of the particles of quarry by-products compared with the spherical shape of fly ash particles. Somewhat lower flowability may also occur when using screenings instead of natural sand. To maintain or improve flowability, additional water and/or other additives (such as coal fly ash, which enhances the flowability of the mix) may be needed. Although chemical admixtures (such as water reducing agents) are not ordinarily added to flowable fill mixtures, the use of an appropriate admixture may also help to improve flowability.

Time of Set: Setting time for flowable fill mixes is determined mainly by the cement and water content of the mix, as well as atmospheric conditions. The use of quarry by-products in mixes is not expected to adversely affect the normal setting time of flowable fill mixes in which they are used, provided the cement content of the mix is not altered. Similarly, if pond fines or baghouse fines are used, the time of set should also not be adversely affected as long as the amount of cement in the mix and the water-cement ratio remains essentially the same.

Bleeding and Shrinkage: The use of screenings to replace sand in flowable fill mixes should have minimal effects on bleeding and shrinkage for these mixes. Likewise, the use of pond fines or baghouse fines in lieu of some fly ash in high fly ash content mixes should also not adversely impact bleeding or shrinkage. Evaporation of bleed water in some mixes (e.g., mixes containing high fly ash content) often results in a shrinkage of approximately 10.4 mm per m (1/8 in per ft) of flowable fill depth.(4)

DESIGN CONSIDERATIONS

Mix Design

In most cases, flowable fill mixes are designed on the basis of a given strength criterion, not on prescribed amounts of ingredients. If quarry by-products are incorporated in these mixes, then specific mix designs will need to be prepared to establish design criteria. The increased fines content in a flowable fill mix when pond fines or baghouse fines are used may require an increase in the water content and/or cement content in order to ensure a flowable mix.(5) With little or no fly ash in the mix, its flowability is likely to be noticeably reduced.

Flowable fill mixtures are usually designed on the basis of compressive strength development, generally after 28 days of ambient temperature curing, but sometimes on the basis of longer term (90 days or more) strength. They are usually designed to have high fluidity (typical slump of 150 mm (6 in) to 200 mm (8 in)). In many applications, especially pipe trench backfills where future access for repairs may become necessary, a maximum unconfined compressive strength (usually in the 690 kPa (100 lb/in^2) to 1035 kPa (150 lb/in^2) range) is the design criteria. For structural support applications, such as abutment backfills supporting bridge approach slabs, the design criteria may range from 4140 kPa (600 lb/in^2) to 8280 kPa (1,200 lb/in^2).

Screenings

When using screenings to replace all or part of the natural sand in flowable fill mixes, the amount of Portland cement and fly ash used should remain essentially the same. The overall density of the flowable fill mix should not be too different when using screenings, since the screenings have a density that is in the same range as natural sand. Some additional water may be needed, compared with the sand mixes, to achieve a desired range of flowability.

Pond Fines or Baghouse Fines

If pond fines or baghouse fines are to replace part or all of the pozzolan, such as fly ash (in high fly ash content mixes), it is possible that a small increase in the amount of Portland cement in the mix may be needed in order to achieve a desired level of compressive strength. The pond fines or baghouse fines may be somewhat denser than fly ash, resulting in a somewhat increased mix density. Some additional water may also be needed to maintain the desired range of flowability.

Structural Design

Structural design procedures for flowable fill materials are no different than geotechnical design procedures for conventional earth backfill materials. The procedures are based on using the unit weight and shear strength of the flowable fill to calculate the bearing capacity and lateral pressure of the material under given site conditions.

CONSTRUCTION PROCEDURES

Material Handling and Storage

The same general methods and equipment used to handle, store, and stockpile conventional aggregates are applicable for quarry by-products.

Mixing, Placing, and Compacting

Flowable fill can be produced at a central concrete mixing plant in accordance with ASTM C94(6) and delivered by concrete truck mixers or using a mobile, volumetric mixer for small jobs. It is important that high fluidity (slump greater than 150 mm (6 in)) be maintained to ensure that the flowable fill material entirely fills all voids beneath pavements and around structures and utilities.

Quality Control

Various standard field and laboratory tests for flowable fill mixes are given by AASHTO T27,(7) as well as ASTM Provisional Standards 28(8) and 29.(9)

UNRESOLVED ISSUES

Quarry by-products are basically untried in field flowable fill applications. Experience is needed in the design, placement, and performance of flowable fill mixes containing different sources of quarry by-products, including some mixes with coal fly ash. Data are also needed on long-term strength development, flowability, and other engineering properties of such mixes.

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ORIGIN

Reclaimed asphalt pavement (RAP) is the term given to removed and/or reprocessed pavement materials containing asphalt and aggregates. These materials are generated when asphalt pavements are removed for reconstruction, resurfacing, or to obtain access to buried utilities. When properly crushed and screened, RAP consists of high-quality, well-graded aggregates coated by asphalt cement.

Asphalt pavement is generally removed either by milling or full-depth removal. Milling entails removal of the pavement surface using a milling machine, which can remove up to 50 mm (2 in) thickness in a single pass. Full-depth removal involves ripping and breaking the pavement using a rhino horn on a bulldozer and/or pneumatic pavement breakers. In most instances, the broken material is picked up and loaded into haul trucks by a front-end loader and transported to a central facility for processing. At this facility, the RAP is processed using a series of operations, including crushing, screening, conveying, and stacking.

Although the majority of old asphalt pavements are recycled at central processing plants, asphalt pavements may be pulverized in place and incorporated into granular or stabilized base courses using a self-propelled pulverizing machine. Hot in-place and cold in-place recycling processes have evolved into continuous train operations that include partial depth removal of the pavement surface, mixing the reclaimed material with beneficiating additives (such as virgin aggregate, binder, and/or softening or rejuvenating agents to improve binder properties), and placing and compacting the resultant mix in a single pass.

Reliable figures for the generation of RAP are not readily available from all state highway agencies or local jurisdictions. Based on incomplete data, it is estimated that as much as 41 million metric tons (45 million tons) of RAP may be produced each year in the United States.(1)

Additional information on recycling of asphalt pavement can be obtained from the following organizations:

National Asphalt Pavement Association
5100 Forbes Boulevard
Lanham, Maryland 20706-4413

Asphalt Institute
Research Park Drive
Lexington, Kentucky 40512

Asphalt Recycling and Reclaiming Association
#3 Church Circle, Suite 250
Annapolis, Maryland 21401

CURRENT MANAGEMENT OPTIONS

Recycling

The majority of the RAP that is produced is recycled and used, although not always in the same year that it is produced. Recycled RAP is almost always returned back into the roadway structure in some form, usually incorporated into asphalt paving by means of hot or cold recycling, but it is also sometimes used as an aggregate in base or subbase construction.

It has been estimated that as much as approximately 33 million metric tons (36 million tons), or 80 to 85 percent of the excess asphalt concrete presently generated, is reportedly being used either as a portion of recycled hot mix asphalt, in cold mixes, or as aggregate in granular or stabilized base materials.(2) Some of the RAP that is not recycled or used during the same construction season that it is generated is stockpiled and is eventually reused.

Disposal

Excess asphalt concrete is disposed of in landfills or sometimes in the right of way. In most situations, this occurs where small quantities are involved, or where the material is commingled with other materials, or facilities are not readily available for collecting and processing the RAP. It is estimated that the amount of excess asphalt concrete that must be disposed is less than 20 percent of the annual amount of RAP that is generated.

MARKET SOURCES

In most cases, recycled hot mix asphalt can be obtained from central RAP processing facilities where asphalt pavements are crushed, screened, and stockpiled for use in asphalt concrete production, cold mix, or as a granular or stabilized base material. Most of these processing facilities are located at hot mix asphalt plant sites, where the RAP is either sold or used as feedstock for the production of recycled hot mix asphalt pavement or recycled cold mix.

The properties of RAP are largely dependent on the properties of the constituent materials and asphalt concrete type used in the old pavement. Since RAP may be obtained from any number of old pavement sources, quality can vary. Excess granular material or soils, or even debris, can sometimes be introduced into old pavement stockpiles. The number of times the pavement has been resurfaced, the amount of patching and/or crack sealing, and the possible presence of prior seal coat applications will all have an influence on RAP composition. Quality control is needed to ensure that the processed RAP will be suitable for the prospective application. This is particularly the case with in-place pavement recycling.

HIGHWAY USES AND PROCESSING REQUIREMENTS

Milled or crushed RAP can be used in a number of highway construction applications. These include its use as an aggregate substitute and asphalt cement supplement in recycled asphalt paving (hot mix or cold mix), as a granular base or subbase, stabilized base aggregate, or as an embankment or fill material.

Asphalt Concrete Aggregate and Asphalt Cement Supplement

Recycled asphalt pavement can be used as an aggregate substitute material, but in this application it also provides additional asphalt cement binder, thereby reducing the demand for asphalt cement in new or recycled asphalt mixes containing RAP.

When used in asphalt paving applications (hot mix or cold mix), RAP can be processed at either a central processing facility or on the job site (in-place processing). Introduction of RAP into asphalt paving mixtures is accomplished by either hot or cold recycling.

Hot Mix Asphalt (Central Processing Facility)

Recycled hot mix is normally produced at a central RAP processing facility, which usually contains crushers, screening units, conveyors, and stackers designed to produce and stockpile a finished granular RAP product processed to the desired gradation. This product is subsequently incorporated into hot mix asphalt paving mixtures as an aggregate substitute. Both batch plants and drum-mix plants can incorporate RAP into hot mix asphalt.

Hot Mix Asphalt (In-Place Recycling)

Hot in-place recycling is a process of repaving that is performed as either a single or multiple pass operation using specialized heating, scarifying, rejuvenating, laydown, and compaction equipment. There is no processing required prior to the actual recycling operation.

Cold Mix Asphalt (Central Processing Facility)

The RAP processing requirements for cold mix recycling are similar to those for recycled hot mix, except that the graded RAP product is incorporated into cold mix asphalt paving mixtures as an aggregate substitute.

Cold Mix Asphalt (In-Place Recycling)

The cold in-place recycling process involves specialized plants or processing trains, whereby the existing pavement surface is milled to a depth of up to 150 mm (6 in), processed, mixed with asphalt emulsion (or foamed asphalt), and placed and compacted in a single pass. There is no processing required prior to the actual recycling operation.

Granular Base Aggregate

To produce a granular base or subbase aggregate, RAP must be crushed, screened, and blended with conventional granular aggregate, or sometimes reclaimed concrete material. Blending granular RAP with suitable materials is necessary to attain the bearing strengths needed for most load-bearing unbound granular applications. RAP by itself may exhibit a somewhat lower bearing capacity than conventional granular aggregate bases.

Stabilized Base Aggregate

To produce a stabilized base or subbase aggregate, RAP must also be crushed and screened, then blended with one or more stabilization reagents so that the blended material, when compacted, will gain strength.

Embankment or Fill

Stockpiled RAP material may also be used as a granular fill or base for embankment or backfill construction, although such an application is not widely used and does not represent the highest or most suitable use for the RAP. The use of RAP as an embankment base may be a practical alternative for material that has been stockpiled for a considerable time period, or may be commingled from several different project sources. Use as an embankment base or fill material within the same right of way may also be a suitable alternative to the disposal of excess asphalt concrete that is generated on a particular highway project.

MATERIAL PROPERTIES

Physical Properties

The properties of RAP are largely dependent on the properties of the constituent materials and the type of asphalt concrete mix (wearing surface, binder course, etc.). There can be substantial differences between asphalt concrete mixes in aggregate quality, size, and consistency. Since the aggregates in surface course (wearing course) asphalt concrete must have high resistance to wear/abrasion (polishing) to contribute to acceptable friction resistance properties, these aggregates may be of higher quality than the aggregates in binder course applications, where polishing resistance is not of concern.

Both milling and crushing can cause some aggregate degradation. The gradation of milled RAP is generally finer and more dense than that of the virgin aggregates. Crushing does not cause as much degradation as milling; consequently, the gradation of crushed RAP is generally not as fine as milled RAP, but finer than virgin aggregates crushed with the same type of equipment.

The particle size distribution of milled or crushed RAP may vary to some extent, depending on the type of equipment used to produce the RAP, the type of aggregate in the pavement, and whether any underlying base or subbase aggregate has been mixed in with the reclaimed asphalt pavement material during the pavement removal.

During processing, virtually all RAP produced is milled or crushed down to 38 mm (1.5 in) or less, with a maximum allowable top size of either 51 mm (2 in) or 63 mm (2.5 in). Table 13-1 lists the typical range of particle size distribution that normally results from the milling or crushing of RAP. Milled RAP is generally finer than crushed RAP. Studies on pavements in California, North Carolina, Utah and Virginia have shown that before and after milling, the pavement fraction passing a 2.36 mm (No. 8) sieve can be expected to increase from a premilled range of 41 to 69 percent to a postmilled range of 52 to 72 percent. The fraction passing a 0.075 mm (No. 200) sieve can be expected to increase from approximately 6 to 10 percent to a range of 8 to 12 percent.(3) Most sources of RAP will be a well-graded coarse aggregate, comparable to, or perhaps slightly finer and more variable than, crushed natural aggregates.

The unit weight of milled or processed RAP depends on the type of aggregate in the reclaimed pavement and the moisture content of the stockpiled material. Although available literature on RAP contains limited data pertaining to unit weight, the unit weight of milled or processed RAP has been found to range from 1940 to 2300 kg/m^3 (120 to 140 lb/ft^3), which is slightly lower than that of natural aggregates.

Table 13-1. Typical range of particle size distribution for reclaimed asphalt pavement (RAP) (percent by weight passing).

Screen Size (mesh)	Percent Finer After Processing or Milling
37.5 mm (1.5 in)	100
25 mm (1.0 in)	95 - 100
19 mm (3/4 in)	84 - 100
12.5 mm (1/2 in)	70 - 100
9.5 mm (3/8 in)	58 - 95
4.75 mm (No. 4)	38 - 75
2.36 mm (No. 8)	25 - 60
1.18 mm (No. 16)	17 - 40
0.60 mm (No. 30)	10 - 35[a]
0.30 mm (No. 50)	5 - 25[b]
0.15 mm (No. 100)	3 - 20[c]
0.075 mm (No. 200)	2 - 15[d]

a. Usually less than 30 percent
b. Usually less than 20 percent
c. Usually less than 15 percent
d. Usually less than 10 percent

Information on the moisture content of RAP stockpiles is sparse, but indications are that the moisture content of the RAP will increase while in storage. Crushed or milled RAP can pick up a considerable amount of water if exposed to rain. Moisture contents up to 5 percent or higher have been measured for stored crushed RAP.(4) As noted earlier, during periods of extensive precipitation, the moisture content of some RAP stockpiles may be as high as 7 to 8 percent.(5) Lengthy stockpiling of crushed or milled RAP should, therefore, be kept to a minimum.

The asphalt cement content of RAP typically ranges between 3 and 7 percent by weight. The asphalt cement adhering to the aggregate is somewhat harder than new asphalt cement. This is due primarily to exposure of the pavement to atmospheric oxygen (oxidation) during use and weathering. The degree of hardening depends on several factors, including the intrinsic properties of the asphalt cement, the mixing temperature/time (increases with increasing high temperature exposure), the degree of asphalt concrete compaction (increases if not well compacted), asphalt cement/air voids content (increases with lower asphalt/higher air voids content), and age in service (increases with age).

The RAP obtained from most wearing surface mixes will usually have an asphalt content in the 4.5 to 6 percent range. The recovered asphalt from RAP usually exhibits low penetration and relatively high viscosity values, depending on the amount of time the original pavement has been in service. Penetration values at 25°C (77°F) are likely to range from 10 to 80 while the absolute viscosity values at 60°C (140°F) may range from as low as 2,000 poises (equivalent to AC-20) up to as high as 50,000 poises or greater, depending on the extent of aging. Viscosity ranges from 4,000 to 25,000 poises can normally be expected from the asphalt cement that is recovered from RAP material.(6)

Table 13-2 provides a summary of the typical ranges of physical (other than gradation) and mechanical properties of RAP.

Table 13-2. Physical and mechanical properties of reclaimed asphalt pavement (RAP).

Type of Property	RAP Property	Typical Range of Values
Physical Properties	Unit Weight	1940 - 2300 kg/m^3 (120-140 lb/ft^3)
	Moisture Content	Normal: up to 5% Maximum: 7-8%
	Asphalt Content	Normal: 4.5-6% Maximum Range: 3-7%
	Asphalt Penetration	Normal: 10-80 at 25°C (77°F)
	Absolute Viscosity or Recovered Asphalt Cement	Normal: 4,000 - 25,000 poises at 60°C (140°F)
Mechanical Properties	Compacted Unit Weight	1600 - 2000 kg/m^3 (100-125 lb/ft^3)
	California Bearing Ratio (CBR)	100% RAP: 20-25% 40% RAP and 60% Natural Aggregate: 150% or higher

Chemical Properties

Mineral aggregates constitute the overwhelming majority (93 to 97 percent by weight) of RAP. Only a minor percentage (3 to 7 percent) of RAP consists of hardened asphalt cement.

Consequently, the overall chemical composition of RAP is essentially similar to that of the naturally occurring aggregate that is its principal constituent.

Asphalt cement is made up of mainly high molecular weight aliphatic hydrocarbon compounds, but also small concentrations of other materials such as sulfur, nitrogen, and polycyclic hydrocarbons (aromatic and/or naphthenic) of very low chemical reactivity. Asphalt cement is a combination of asphaltenes and maltenes (resins and oils). Asphaltenes are more viscous than either resins or oils and play a major role in determining asphalt viscosity. Oxidation of aged asphalt causes the oils to convert to resins and the resins to convert to asphaltenes, resulting in age hardening and a higher viscosity binder.(7)

Mechanical Properties

The mechanical properties of RAP (see Table 13-2) depend on the original asphalt pavement type, the method(s) utilized to recover the material, and the degree of processing necessary to prepare the RAP for a particular application. Since most RAP is recycled back into pavements, there is a general lack of data pertaining to the mechanical properties for RAP in other possible applications.

The compacted unit weight of RAP will decrease with increasing unit weight, with maximum dry density values reported to range from 1600 kg/m^3 (100 lb/ft^3) to 2000 kg/m^3 (125 lb/ft^3).(8) California Bearing Ratio (CBR) values for RAP material containing trap rock aggregate have been reported in the 20 to 25 percent range. However, when RAP is blended with natural aggregates for use in granular base, the asphalt cement in the RAP has a significant strengthening effect over time, such that specimens containing 40 percent RAP have produced CBR values exceeding 150 percent after 1 week.(9)

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INTRODUCTION

Reclaimed asphalt pavement (RAP) can be used as an aggregate in the hot recycling of asphalt paving mixtures in one of two ways. The most common method (conventional recycled hot mix) involves a process in which RAP is combined with virgin aggregate and new asphalt cement in a central mixing plant to produce new hot mix paving mixtures.(1) A second method (hot in-place recycling) involves a process in which asphalt pavement surface distress is corrected by softening the existing surface with heat, mechanically removing the pavement surface, mixing it with a recycling or rejuvenating agent, possibly adding virgin asphalt and/or aggregate, and replacing it on the pavement without removing the recycled material from the pavement site.(2)

PERFORMANCE RECORD

Although some form of pavement recycling had been practiced as early as 1915,(3) the first sustained efforts to recover and reuse old asphalt paving materials were conducted during 1974 in Nevada and Texas.(4) Bolstered by the sponsorship of the Federal Highway Administration (FHWA), more than 40 states performed and documented RAP demonstration projects between 1976 and 1982.

RAP is now routinely accepted in asphalt paving mixtures as an aggregate substitute and as a portion of the binder in nearly all 50 states. Substitution rates of 10 to 50 percent or more, depending on state specifications, are normally introduced in pavements, and recently developed technology has even made it possible to recycle 90 to 100 percent RAP in hot mix.

Conventional Recycled Hot Mix

The use of processed RAP to produce conventional recycled hot mix (RHM) is the most common type of asphalt recycling and is now considered standard asphalt paving practice. There are abundant technical data available indicating that properly specified and produced recycled hot mix asphalt is equivalent in quality and structural performance to conventional hot mix asphalt in terms of rutting, raveling, weathering, and fatigue cracking. Recycled hot mix asphalt mixtures also generally age more slowly and are more resistant to the action of water than conventional hot mix asphalt. (See references 5,6,7,8,9,10, and 11.)

The maximum limit for RAP content in RHM produced in conventional hot mix asphalt batch plants is widely considered to be 50 percent, limited by both the heat capacity of the plants and gaseous hydrocarbon emissions. As much as 60 to 70 percent RAP may be processed in drum-mix plants. Special plants based on microwave technology have been developed to limit gaseous emissions from hot mix asphalt production using very high RAP contents (up to 100 percent RAP), but the cost of heating is much higher than that of conventional systems. This process was developed in California and has only seen limited use.(12)

Table 13-3 provides a 1996 list of State Department of Transportation (DOT) specification requirements for the use of RAP in hot mix asphalt paving mixtures. Separate requirements are given for mixes produced in batch plants or drum-mix plants. Maximum allowable RAP percentages are shown in Table 13-3 for wearing surface, binder, and base courses.(13)

Table 13-3. State DOT specification requirements for the use of reclaimed asphalt pavement (RAP) in hot mix asphalt paving mixtures.(13)

State	Max. RAP % – Batch Plants			Max. RAP % – Drum Plants			Top Size for RAP
	Base	Binder	Surface	Base	Binder	Surface	
Alabama	40	40	15	50	50	15	2 in
Alaska	–	–	–	–	–	–	–
Arizona	30	30	30	30	30	30	1.5 in
Arkansas	70	70	70	70	70	70	3 in
California	50	50	50	50	50	50	2 in
Colorado	15	15	15	15	15	15	1.5
Connecticut	40	40	40	40	40	40	2 in
Delaware	35	35	25	50	50	30	2 in
Florida	60	50	None	60	50	None	Specs
Georgia	25	25	25	40	40	40	2 in
Hawaii	30	None	None	40	None	None	1.5 in
Idaho	Open	Open	Open	Open	Open	Open	2 in
Illinois	50	25	15	50	25	15	Specs
Indiana	50	50	20	50	50	20	2 in
Iowa	Open	Open	Open	Open	Open	Open	1.5 in
Kansas	50	50	50	50	50	50	2 in
Kentucky	30	30	30	30	30	30	Specs
Louisiana	30	30	None	30	30	None	2 in
Maine	40	40	None	40	40	None	1 in
Maryland	Open	Open	Limit	Open	Open	Limit	Specs

Table 13-3. State DOT specification requirements for the use of reclaimed asphalt pavement (RAP) in hot mix asphalt paving mixtures (continued).(13)

State	Max. RAP % – Batch Plants			Max. RAP % – Drum Plants			Top Size for RAP
	Base	Binder	Surface	Base	Binder	Surface	
Massachusetts	20	20	10	40	40	10	.75 in
Michigan	50	50	50	50	50	50	Specs
Minnesota	59	50	30	50	50	30	3 in
Mississippi	30	30	15	30	30	15	2 in
Missouri	50	50	50	50	50	50	1.5 in
Montana	50	50	10	50	50	10	2 in
Nebraska	Not Used	Not Used	Not Used	Open	Open	Open	2 in
Nevada	50	50	15	50	50	15	1.5 in
New Hampshire	35	35	15	50	50	15	Specs
New Jersey	25	25	10	25	25	10	2 in
New Mexico	Open	Open	Open	Open	Open	Open	1.5 in
New York	50	50	None	70	70	None	2 in
North Carolina	60	60	60	60	60	60	2 in
North Dakota	50	50	50	50	50	50	1 in
Ohio	50	35	20	50	35	20	2 in
Oklahoma	25	25	None	25	25	None	2 in
Oregon	30	20	20	30	20	20	1 in
Pennsylvania	Open	Open	Open	Open	Open	Open	2 in
Rhode Island	30	30	None	30	30	None	1.25 in
South Carolina	30	25	20	30	25	20	2 in
South Dakota	Not Used	Not Used	Not Used	50	50	50	1.5 in
Tennessee	15	Open	None	Open	Open	None	Open
Texas	15	Open	Open	Open	Open	Open	2 in
Utah	Not Used	Not Used	Not Used	25	25	25	2 in
Vermont	Specs.	Specs.	Specs	Specs	Specs	Specs	Specs
Virginia	25	25	25	25	25	25	2 in Open
Washington	Open	Open	Open	Open	Open	Open	Open
West Virginia	Open	Open	Open	Open	Open	Open	Open
Wisconsin	Open	35	20	Open	35	20	Open
Wyoming	50	50	50	50	50	50	2 in

While all state highway agencies permit the use of RAP in base and binder courses, 10 agencies do not permit the use of RAP in surface courses. These include Alaska, Florida, Hawaii, Louisiana, Maine, Maryland, New York, Oklahoma, Rhode Island, and Tennessee. Louisiana and Maine allow up to 20 percent RAP in shoulder mixes only. Massachusetts does not permit the use of RAP in open-graded friction course mixes.(13) Minnesota permits RAP to be used in surface mixes only on low-volume roads.(5) Oklahoma allows up to 25 percent RAP for low-volume roads (fewer than 1,000 vehicles per day) only. Oregon does not permit RAP use in surface mixes on interstate highways.(13)

States that approve the use of RAP in surface courses generally permit from 10 to 30 percent RAP. Some states permit even higher percentages from approved RAP sources. Allowable binder and base course aggregate substitution rates range from 10 to as high as 70 percent in one state (Arkansas). At least 22 states do not permit the blending or commingling of RAP from different projects into combined stockpiles.(13)

Hot In-Place Surface Recycling

The use of hot in-place recycling (HIPR) has developed rapidly over the past decade, although it is in use only on a limited basis. Simple heater-scarification units, heat reforming systems, and special techniques have been developed for heating, scarifying, rejuvenation, and remixing of up to 50 mm (2 in) in depth of aged old asphalt pavement to new hot mix quality overlay in one pass.

The Asphalt Recycling and Reclaiming Association (ARRA) recognizes three basic HIPR processes: (1) heater-scarification (multiple pass); (2) repaving (single pass); and (3) remixing.

The first two processes involve removal, rejuvenation, and replacement of the top 25 mm (1 in) of the existing pavement. The remixing process involves incorporating virgin hot mix with the recycled paving material in a pugmill and placement to a depth of 50 mm (2 in). The major advantage of HIPR is the cost savings that it can potentially achieve over conventional recycled hot mix, eliminating the costs associated with transporting, processing and stockpiling RAP. Since only the top 50 mm (2 in) of pavement can normally be reconditioned using this process, HIPR applications are limited to roadways that do not have any structural deficiencies and do no not require additional materials. The major disadvantage of HIPR is the inability to make significant changes to the mix. Pavements that exhibit structural base failure, irregular patching or the need for major drainage or grade improvements are not suitable candidates for HIPR.(2)

Not all states have experience in HIPR applications, although HIPR technology is a fairly well accepted practice. There are 32 states that report having some experience with HIPR, although

22 of these states consider their use of HIPR to be experimental. The 10 states that have the most experience with HIPR are Arkansas, Colorado, Florida, Kansas, Maryland, New York, Ohio, Texas, Utah, and Virginia. None of these states has had more than five HIPR projects per year. A survey of these states found that, in general, all have reported good or fair performance.(2)

The survey of HIPR experience at the state DOT level further indicated that the use of the three different HIPR processes has been fairly evenly divided, with 13 states having had some experience with heater-scarification, and 16 states each having some experience with either the repaving or the remixing process. Of the 10 states with the most HIPR experience, 5 have used heater-scarification, 4 have used the repaving process, and 6 have used the remixing process.(2)

MATERIAL PROCESSING REQUIREMENTS

Recycled Hot Mix

Reclaimed asphalt pavement must be processed into a granular material prior to use in hot mix applications. A typical RAP processing plant consists of a crusher, screening units, conveyors, and stacker. It is desirable to produce either a coarse or a fine fraction of processed RAP to permit better control over input to the hot mix plant and better control of the mix design. The processed RAP used in recycled hot mix asphalt should be as coarse as possible and the fines (minus 0.075 mm (No. 200 sieve)) minimized. Gentle RAP crushing (controlled crusher speed and clearance adjustment on exit gate) is recommended to minimize the fracture of coarse aggregate and excess fines generation.

Hot In-Place Surface Recycling

In the HIPR process, the surface of the pavement must be softened with heat prior to mechanical scarification. The HIPR process has evolved into a self-contained, continuous train operation that includes heating, scarifying, rejuvenator addition, mixing, and replacement.

ENGINEERING PROPERTIES

Some of the engineering properties of RAP that are of particular interest when RAP is incorporated into new asphalt pavements include its gradation, asphalt content, and the penetration and viscosity of the asphalt binder.

Gradation: The aggregate gradation of processed RAP is somewhat finer than virgin aggregate. This is due to mechanical degradation during asphalt pavement removal and processing. RAP aggregates usually can satisfy the requirements of ASTM D692 "Coarse Aggregates for Bituminous Pavement Mixtures" and ASTM D1073 "Fine Aggregate for Bituminous Pavement Mixtures."(14,15)

Asphalt Content and Properties: The asphalt content of most old pavements will comprise approximately 3 to 7 percent by weight and 10 to 20 percent by volume of the pavement. Due to oxidation aging, the asphalt cement has hardened and consequently is more viscous and has lower penetration values than the virgin asphalt cement. Depending on the amount of time the original pavement had been in service, recovered RAP binder may have penetration values from 10 to 80 and absolute viscosity values at 60°C (140°F) in a range from as low as 2,000 poises to as high 50,000 poises or greater.(16)

DESIGN CONSIDERATIONS

Conventional Recycled Hot mix

Mix Design

The use of processed RAP in hot mix asphalt pavements is now standard practice in most jurisdictions and is referenced in ASTM D3515.(17) The primary steps in the design of mixes include the determination of material properties of RAP and new materials, the selection of an appropriate blend of RAP and virgin aggregate to meet gradation, the selection of an appropriate asphalt cement blend to satisfy specified viscosity and/or penetration requirements, the need to add a recycling or rejuvenating agent to soften the existing binder, and the need to comply with stability, flow, and air voids requirements.

Either the Marshall(18) or the Hveem(19) mix design procedures are used by most state agencies for determining the asphalt cement and acceptable RAP content of recycled paving mixes.(1)

Recycling and rejuvenating agents can be divided into three main types: "super-soft" asphalt cements, napthenic (aromatic) oils, and paraffinic oils. These products consist of organic compounds derived from petroleum extracts during petroleum hydrocarbon processing. ASTM D4552(20) provides a classification of recycling or rejuvenating agents.

Procedures for selecting the quality of asphalt cement or recycling agent are outlined in ASTM D4887.(21) This specification includes a viscosity blending chart, which enables the designer to determine the percentage of recycling or rejuvenating agent (or soft asphalt cement) to add to the total binder in order to achieve a desired value of absolute viscosity for the recycled asphalt cement. The Asphalt Institute's manual on asphalt hot mix recycling also provides trial mix design examples that indicate how to use a viscosity blending chart to design a recycled hot mix.

The Asphalt Institute suggests that when 20 percent or less RAP is used in a mix, no change in asphalt grade is required. However, for mixes with greater than 20 percent RAP, a drop in one grade (softer asphalt cement) is recommended to compensate for the greater viscosity of the oxidized binder.(1) Many states use the same grade of asphalt cement regardless of the RAP content.

The Asphalt Institute's manual on mix design methods for asphalt concrete(22) provides a method to determine necessary mix design characteristics (such as stability, flow, and air voids content) for either the Marshall or the Hveem mix design methods. The final mix design proportions for the recycled hot mix paving mixture will be determined by completing mix design testing using standard procedures to satisfy applicable mix design criteria.

Additional virgin aggregates may be required to satisfy gradation requirements to improve stability and to limit the RAP content in recycled hot mixes. In the production of hot mix, superheated virgin aggregate is needed to provide indirect heat transfer to the RAP while maintaining the proper mix temperature without the generation of "blue smoke."

Structural Design

Conventional AASHTO pavement structural design methods are appropriate for asphalt pavements incorporating reclaimed asphalt pavement in the mix.

Hot In-Place Recycling

Mix Design

Mix design procedures for HIPR are not as well established as those for conventional recycled hot mix. Many states as a minimum require that cores be taken of the candidate pavement to determine in-place pavement properties, including binder content, viscosity, and aggregate grading.(2)

The material properties of the existing asphalt pavement (to at least the depth of scarification) should be determined prior to construction in order to permit any necessary adjustments to aggregate gradation to develop the required voids in mineral aggregate (VMA) and selection of the appropriate viscosity binder. This will require coring of the pavement to be recycled and laboratory testing of the recovered paving samples.

Unlike conventional recycled hot mix where the RAP is combined with a significant amount of new aggregate material (making up typically between 60 to 80 percent of the RHM), HIPR may involve up to 100 percent recycling of the existing pavement. Consequently, the extent to which the existing pavement can be improved or modified is limited by the condition and characteristics of the old mix.

The amount of rejuvenating agent that can be added through HIRP is limited by the air voids content of the existing asphalt. When the air voids content of the old asphalt mix is too low to accommodate sufficient recycling agent for proper rejuvenation or softening of the old asphalt binder without mix flushing, it may be necessary to add additional fine aggregate or to beneficiate with virgin hot mix to open up the mix or increase the air voids. The selection of the appropriate addition (either fine aggregate or virgin hot mix), and the amount to be added, are determined by Marshall or Hveem mix design methods.

The type of recycling or rejuvenating agent and the percentage to be added to the binder can be estimated using procedures outlined in ASTM methods D4552(20) and D4887.(21) The recycling or rejuvenating agent, if used, should be compatible with the recycled and new asphalt binder.

Structural Design

HIPR is generally considered a rehabilitation technique for addressing superficial pavement distress to a maximum depth of about 50 mm (2 in). The recycled layer is considered to be structurally equivalent to new hot mix asphalt.

CONSTRUCTION PROCEDURES

Recycled Hot Mix

Material Handling and Storage

RAP is produced by milling, ripping, breaking, crushing, or pulverizing types of equipment. To ensure that the final RAP product will perform as intended, inspection of incoming RAP with rejection of contaminated loads (excess granular material, surface treatment, joint sealant, etc.) should be undertaken. Some jurisdictions also require that RAP from a particular project not be blended or commingled with RAP from other projects.

Once processed, RAP can be handled and stored as a conventional aggregate material. However, because of the variability of RAP in comparison with virgin aggregates, many agencies do not permit the blending of RAP from different projects into combined stockpiles. The Asphalt Institute recommends that the height of RAP stockpiles be limited to a maximum of 3 meters (10 ft) to help prevent agglomeration or sticking together of the RAP particles.(1) Stockpiling time should also be minimized to keep the moisture content of RAP stockpiles from becoming excessive.

Experience has proven that conical stockpiles are preferred to horizontal stockpiles and will not cause RAP to re-agglomerate in large piles. RAP has the tendency to form a crust (due to a solar/thermal effect from the sun) over the first 200 to 250 mm (8 to 12 in) of pile depth for both conical and horizontal stockpiles. This crust tends to help shed water, but is easily broken by a front-end loader, and may help keep the rest of the pile from agglomerating. RAP has a tendency to hold water and not to drain over time like an aggregate stockpile. Therefore, low, horizontal, flat stockpiles are subject to greater moisture accumulation than tall, conical stockpiles. It is not unusual to find RAP moisture content in the 7 to 8 percent range during the rainy season at facilities using low, horizontal stockpiling techniques.(23)

RAP stockpiles are typically left uncovered because covering with tarps can cause condensation under the tarp and add moisture to the RAP stockpile. For this reason, RAP stockpiles are either left uncovered or RAP is stored in an open-sided building, but under a roof.(23)

When large quantities of RAP from different sources are available, it is advisable to keep stockpiles separated and identified by source. Consistent RAP from a "composite" or "blended" pile can be produced using a crushing and screening operation and reprocessing stockpiles that come to the yard from different sources. Material handling machinery, such as front-end loaders and bulldozers, should be kept from driving directly on the stockpile. Agglomerating RAP particles can make it very difficult for the loader to handle the RAP.

Mixing, Placing and Compacting

When RAP is added to hot mix asphalt, measures must be taken to avoid exposing the RAP to temperatures in excess of 427°C (800°F). Exposure of the RAP to temperatures above this limit can result in excessive hydrocarbon emissions (blue smoke). To reduce this problem, hot mix asphalt plants have been modified to permit the recycling of RAP.(24)

In a batch plant operation, the RAP is usually added to superheated new aggregate at the pugmill. In drum-mix plants, RAP is usually introduced with new aggregate into the drum using a dual feed system. The new aggregate is typically introduced at the hot end of the drum (normally the front end of the drum), while the RAP is introduced at the middle or rear of the drum to prevent overheating damage to the RAP.(25)

In a batch plant, typical RAP substitution rates are limited by the heat capacity of the plant and the ability to superheat the aggregate to temperatures that will produce a suitable mix temperature. This normally limits batch plant blends to between 10 and 30 percent RAP. In a drum mix plant, from 30 to 70 percent RAP can be added, with a practical limit of 50 percent, due to hydrocarbon emission limitations that may be exceeded if excess RAP is introduced.

Quality Control

To produce consistently high-quality recycled hot mix asphalt, the need for systematic quality control of the RAP is essential. The process should be monitored for processed RAP moisture content, gradation, and asphalt cement content.(26) Controlled plant operations have been developed to produce a consistent (homogeneous) RAP. Extraction tests to monitor the RAP gradation and asphalt cement content, and penetration and viscosity tests on the recovered asphalt cement, should be performed regularly to monitor the RAP characteristics for comparison with the job mix formula and enable appropriate adjustments to the mix.

The same field testing procedures used for conventional hot mix asphalt mixes should be used for mixes containing reclaimed asphalt pavement. Mixes should be sampled in accordance with AASHTO T168,(27) and tested for specific gravity in accordance with ASTM D2726(28) and in-place density in accordance with ASTM D2950.(29)

Hot In-Place Recycling

Mixing, Placing and Compacting

There are three basic HIPR construction processes in use: heater scarification, repaving, and remixing. All involve a specialized plant in a continuous train operation.

Heater scarification involves a plant that heats the pavement surface (typically using propane radiant heaters), scarifies the pavement surface using a bank of nonrotating teeth, adds a liquid rejuvenating additive, then mixes and levels the recycled mix using a standard auger system. The recycled asphalt pavement is then compacted using conventional compaction equipment. The process is limited in its ability to repair severely rutted pavements, which are often overlaid with conventional hot mix asphalt.

Repaving is a more sophisticated process that includes removing (by heating and scarification and/or grinding) the top 25 to 50 mm (1 to 2 in) of the old asphalt pavement, adding and mixing in a rejuvenating agent to improve asphalt viscosity, placing the recycled material as a leveling course using a primary screed, and simultaneously placing a thin (usually less than 25 mm (1 in) but up to 50 mm (2 in) in some systems) hot mix asphalt overlay. Conventional equipment and procedures are used immediately behind the train to compact both layers of material to ensure a monolithic bond between the new and recycled layer.(30)

The remixing process is used when additional aggregates are required to improve the strength or stability of the recycled asphalt concrete. Scarified or milled RAP is blended with rejuvenator and new virgin aggregate or new hot mix asphalt, then placed by a compacting screed. Conventional equipment and procedures are used to place and compact the remixed material.

Quality Control

The initial step in the quality control of hot in-place recycled mixes is in the selection of the pavement to be recycled. Not all pavements are good candidates for this type of recycling. Cores of the pavement being considered for HIPR must be taken during the early planning for the project. The cores should first be visually examined for pavement problems such as delaminations, stripping, or stripping potential, or water in the voids or delaminations. Pavements with delaminations, especially saturated delaminations, in the top 5 cm (2 in) should not be considered for HIPR projects. Also, pavements that have been rutted, heavily patched, or chip-sealed are not good candidates for HIPR projects.

Next, as noted in the Mix Design section, field core specimens should be analyzed in the laboratory to determine (based on the asphalt content, viscosity, and penetration of the recovered binder) the required amount of rejuvenating agent to be added to the mix in order to attain the desired viscosity of the recycled mix. If too much rejuvenating agent (1.0 percent or more by weight of mix) must be added in order to attain this viscosity, the mix should probably not be recycled in place. As a guideline, pavements being considered for HIPR should not be too severely aged. It is recommended that such pavements have an absolute viscosity lower that 200,000 poises (and preferably below 100,000 poises) in order to be considered for HIPR projects.(31)

Field core specimens should also be evaluated for air voids content during the pavement selection process. An existing pavement being considered for HIPR should have an air voids content in excess of 6 percent, in order to accommodate the addition of a rejuvenating agent without the loss of stability in the recycled mix. If material properties are not completely satisfactory for 100 percent recycling, the addition of 20 to 30 percent by weight of virgin hot mix during recycling should be considered.(31)

Field quality control measures during HIPR operations include monitoring the depth of scarification, the temperature of the recycled mix, the visual appearance and homogeneity of the scarified or milled RAP, the compaction procedure, and the visual appearance of the recycled pavement surface after compaction. Loose samples of the recycled mix should be obtained and extraction tests performed to monitor RAP gradation, asphalt cement and air voids contents, and penetration and viscosity of the recovered asphalt binder for comparison with the job mix formula.(32) The recycled mix should be monitored for in-place density in accordance with ASTM D2950.(29)

UNRESOLVED ISSUES

While the asphalt pavement recycling technologies are well established, there is still considerable need for additional performance information, particularly with regard to creep (rutting resistance), fatigue endurance and durability, and the use of reclaimed asphalt pavement in premium surface course mixes. There is also a need for more correlation of field and laboratory measurements to refine guidelines for laboratory prediction of field performance (for instance, laboratory curing procedures that best simulate field conditions).

Some additional issues that require resolution include:

- further information on the variability of RAP, especially from blended stockpiles;
- validation of SUPERPAVE mix design procedures with mixtures containing RAP;
- an environmental code of practice regarding gaseous emissions from hot mix plant recycling and HIPR;
- the suitability of HIPR for surface-treated and rubberized materials (environmental considerations); and
- evaluation methodologies for structural characterization of HIPR asphalt concrete and CIPR asphalt concrete.

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RECLAIMED ASPHALT PAVEMENT

User Guideline

Asphalt Concrete (Cold Recycling)

INTRODUCTION

Reclaimed asphalt pavement (RAP) can be used as an aggregate in the cold recycling of asphalt paving mixtures in one of two ways. The first method (cold mix plant recycling) involves a process in which RAP is combined with new emulsified or foamed asphalt, a recycling or rejuvenating agent, and possibly also with virgin aggregate, and mixed at a central plant or a mobile plant to produce cold mix base mixtures.(1) The second, more common, method involves a process in which the asphalt pavement is recycled in-place (cold in-place recycling (CIPR) process), where the RAP is combined (without heat) with new emulsified or foamed asphalt and/or a recycling or rejuvenating agent, and possibly also with virgin aggregate, and mixed at the pavement site, at either partial depth or full depth, to produce a new cold mix end product.(2) Most states have used cold in-place recycling in conjunction with a hot mix overlay or chip seal.

PERFORMANCE RECORD

Documented performance of cold plant mix recycling projects is not widely available. According to a 1994 survey of all state transportation agencies, at least 32 states have used or are using RAP in cold recycling of asphalt pavements.(3) Although cold recycling has been reportedly practiced in these states, data are unavailable to differentiate whether cold plant mix recycling, CIPR, or both, are being used. In all likelihood, CIPR is probably being utilized more frequently, especially on low-volume roads where transport costs to plant sites are likely to be higher.

The states that appear to have had the most experience with CIPR techniques include California, Indiana, Kansas, New Mexico, Oregon, and Pennsylvania. The performance of CIPR projects in Indiana has been described as structurally comparable to those of cold mixes in which conventional aggregates and asphalt emulsions have been used.(4) Over 800 lane-km (500 lane-miles) of roadways in New Mexico have been successfully recycled using CIPR, and the extensive recycling experiences in California and Pennsylvania have also been very promising.(5) There have been approximately 672 km (420 mi) of low-volume roads in Oregon that were cold in-place recycled between 1984 and 1989, and over 75 percent of these projects were rated fair or better.(6) The performance of eight CIPR projects located throughout Pennsylvania were considered good to satisfactory, as long as a double seal coat was placed over the recycled cold mix.(7)

Performance studies indicate that CIPR retards or eliminates the occurrence of reflective cracking from environmental distress, depending on the depth of treatment and crack depth.(8)

Improper emulsion application can result in high residual asphalt content (leading to flushing) and excessive processing can result in high fines content (leading to rutting due to low stability).

MATERIAL PROCESSING REQUIREMENTS

Cold Plant Mix Recycling

Processing requirements for cold mix recycling are similar to those for recycled hot mix. Recycled asphalt pavement must be processed into a granular material prior to use in cold mix applications. A typical RAP plant consists of a crusher, screening units, conveyors, and stackers.

Cold In-Place Recycling

CIPR (like hot in-place recycling (HIPR)), requires a self-contained, continuous train operation that includes ripping or scarifying, processing (screening and sizing/crushing unit), mixing of the milled RAP, and the addition of liquid rejuvenators. Special asphalt-derived products such as cationic, anionic, and polymer modified emulsions, rejuvenators and recycling agents have been developed especially for CIPR processes. These hydrocarbon materials are sometimes, but not always, used to soften or lower the viscosity of the residual asphalt binder in the RAP material so that it is compatible with the newly added binder.

ENGINEERING PROPERTIES

Some of the engineering properties of RAP that are of particular interest when RAP is used in cold recycled applications include its gradation, asphalt content, and the penetration and viscosity of the asphalt binder.

<u>Gradation</u>: The aggregate gradation of processed RAP is somewhat finer than virgin aggregate. This is due to mechanical degradation during asphalt pavement removal and processing. RAP aggregates usually can satisfy the requirements of ASTM D692 for coarse aggregate and ASTM D1073 for fine aggregate.(9,10)

<u>Asphalt Content</u>: The asphalt content of most old pavements will comprise approximately 3 to 7 percent by weight and 10 to 20 percent by volume of the pavement. Due to oxidation aging, the asphalt cement has hardened and consequently is more viscous and has lower penetration values than the virgin asphalt cement.

Penetration and Viscosity: Depending on the amount of time the original pavement had been in service, recovered RAP binder may have penetration values from 10 to 80 and absolute viscosity values at 60°C (140°F) in a range from as low as 2,000 poises to as high 50,000 poises or greater.(11)

DESIGN CONSIDERATIONS

To satisfy the engineering requirements for use in cold recycled asphalt concrete pavements, it is usually necessary to rejuvenate or augment the asphalt binder in RAP to lower the viscosity and/or increase penetration. This is done by the addition of one or more recycling agents, consisting of either an emulsified or foamed asphalt and/or a rejuvenating agent. Some additional aggregate may also be added to adjust the mix gradation or air voids content.

Cold Plant Mix Recycling

Mix Design

The specifications and design of cold plant mix recycling of asphalt pavements are referred to in ASTM D4215.(12) Cold plant mixtures can be dense-graded or open-graded. Cold-laid asphalt mixes may be used for surface, base, or subbase courses.

Although there are no universally accepted mix design methods for cold mix recycling, the Asphalt Institute recommends and most agencies use a variation of the Marshall mix design method.(13) General procedures include a determination of the aggregate gradation and asphalt content of the processed RAP, determination of the percentage (if any) of new aggregate to be added, calculation of combined aggregate in recycled mix, selection of the type and grade of new asphalt, determination of the asphalt demand of the combined aggregate, estimation of the percent of new asphalt required in the mix, and adjustment of asphalt content by field mix trials.(14)

The percent asphalt demand of combined aggregates can be determined by means of a formula that takes into account the various sieve size fractions of the combined RAP and virgin aggregate. These size fractions include the percentage retained on the 2.36 mm (No. 8) sieve, the percentage between the 2.36 mm (No. 8) and 0.075 mm (No. 200) sieves, and the percentage passing the 0.075 mm (No. 200) sieve. The percent of new asphalt is the difference between the percent asphalt demand and the percent of asphalt contained in the RAP.(1) Using the determined asphalt content, Marshall specimens can be prepared at various emulsion percentages to determine an optimum asphalt content on the basis of applicable stability and air voids criteria.

Structural Design

The AASHTO Design Guide(15) is applicable to recycled cold mix paving mixtures. While there are no universally accepted structural layer coefficient values for asphalt cold mix, it is generally recognized that cold mix asphalt is not the structural equivalent of hot mix asphalt, but is superior to gravel or crushed stone base courses. Asphalt cold mix is generally not recommended for use as a wearing surface, but only in base course layers because of both structural and durability considerations. The structural capacity of recycled cold mix can be considered equal to that of conventional cold mix paving materials.(16)

Although most agencies have not published structural layer coefficient values for conventional or recycled cold mixes, a layer coefficient value of 0.25 to 0.35 for an asphalt stabilized base is considered within a reasonable range. Pennsylvania DOT has assigned a structural layer coefficient of 0.30 for a bituminous-aggregate stabilized base,(7) which is a conventional cold mix.

Cold In-Place Recycling

Mix Design

The Asphalt Institute has recommended a modified Marshall mix type procedure for the design of CIPR mixes.(13) Such a design initially involves obtaining samples of the candidate pavement to determine the gradation of the aggregate, the asphalt content, and the penetration and viscosity of the asphalt binder. Marshall specimens are prepared at various emulsion percentages, as initially determined by calculating the asphalt demand on the basis of aggregate gradation and deducting the percentage of asphalt in the RAP.(16) The optimum asphalt content can be determined by a stability and air voids analysis, with target air voids in the 8 to 10 percent range, or the specimens may be evaluated using indirect tensile strength or resilient modulus testing.(17)

It has recently been shown that the addition of virgin aggregates (20 to 25 percent) in the CIPR process results in less voids and, consequently, less flushing, and improved stability.(14) The amount of recycling agent (either new asphalt or modifying oil) also has a significant effect on the behavior of the mix, with the ideal range of recycling agent being somewhere between 2 and 3 percent by weight of dry RAP.(18)

Structural Design

CIPR is generally considered for rehabilitation of pavements showing distress to depths about 100 to 150 mm (4 to 6 in). It can handle a pavement section in poorer condition and with more cracking than HIPR, provided that the pavement section (when recycled) is structurally sound and adequately drained.

The AASHTO Design Guide (15) is recommended for the thickness design of cold in-place recycled asphalt mixes. Since there is essentially little or no difference in the composition and structural properties of recycled cold mix and cold in-place recycled paving materials, the range of structural layer coefficients recommended for recycled cold mixes (0.25 to 0.35) are also applicable for cold in-place recycled mixes. CIPR mixes are not recommended for use as a wearing surface.

CONSTRUCTION PROCEDURES

Cold Plant Mix Recycling

Material Handling and Storage

RAP is produced by milling, ripping, breaking, crushing, or pulverizing types of equipment. To ensure that the final RAP product will perform as intended, inspection of incoming RAP and rejection of contaminated loads (excess granular material, surface treatment, joint sealant, etc.) should be undertaken. Some jurisdictions also require that RAP from a particular project not be blended or commingled with RAP from other projects.

Once processed, RAP can be handled and stored as a conventional aggregate material. However, because of the variability of RAP in comparison with virgin aggregates, many agencies do not permit the blending of RAP from different projects into combined stockpiles. The Asphalt Institute recommends that the height of RAP stockpiles be limited to a maximum of 3 meters (10 ft) to help prevent agglomeration of the RAP particles.(19)

Experience has proven that conical stockpiles are preferred to horizontal stockpiles and will not cause RAP to re-agglomerate or congeal in large piles. RAP has the tendency to form a crust (due to a solar/thermal effect from the sun) over the first 200-250 mm (8 to 12 in) of pile depth for both conical and horizontal stockpiles. This crust tends to help shed water, but is easily broken by a front-end loader and may help keep the rest of the pile from agglomerating. RAP has a tendency to hold water and not to drain over time like an aggregate stockpile. Therefore, low, horizontal, flat stockpiles are subject to greater moisture accumulation than tall, conical stockpiles. It is not unusual to find RAP moisture content in the 7 to 8 percent range during the rainy season at facilities using low, horizontal stockpiling techniques.(20)

RAP stockpiles are typically left uncovered because covering with tarps can cause condensation under the tarp and add moisture to the RAP stockpile. For this reason, RAP stockpiles are either left uncovered or RAP is stored in an open-sided building, but under a roof.(20)

When large quantities of RAP from different sources are available, it is advisable to keep stockpiles separated and identified by source. Consistent RAP from a "composite" or "blended" pile can be produced using a crushing and screening operation and reprocessing stockpiles from different sources. Material handling machinery, such as front-end loaders and bulldozers, should be kept from driving directly on the stockpile. Agglomeration can result, making it very difficult for the loader to handle the RAP.

Mixing, Placing, and Compacting

The RAP processing requirements for cold mix recycling are similar to those for recycled hot mix, except that the graded RAP product is incorporated into cold mix asphalt paving mixtures as an aggregate substitute. RAP is mixed with new aggregate and emulsified or foamed asphalt in either a central plant or a mobile plant. The blend is then placed as conventional cold mix asphalt. The pavement removal or milling is performed with a self-propelled rotary drum cold planing machine with RAP transferred to trucks for removal from the job site. Cold mix asphalt is usually placed on low-volume roadways with traffic volumes less than 3,000 vehicles per day and covered with either a double surface treatment or a hot mix wearing surface.(21)

Cold plant mix recycling can be accomplished either by hauling the RAP to a central processing location, where it is crushed, screened, and blended with a recycling agent in a central mixing plant, or the RAP can be processed at the project site and prepared in a mobile mixing plant that has been transported to the job site. In either case, a pugmill mixing plant is commonly used.(24)

Recycled cold mix material can be normally placed with a conventional paver, provided the mixing moisture can be adequately controlled to a level not requiring aeration. Cold mix pavement construction requires several warm days and nights for adequate curing.(6) Successful placement using conventional pavers requires that the mix be sufficiently fluid to avoid tearing. Alternatively, a Jersey or towed spreader can be used. Using a Jersey or towed spreader (which is essentially a front-wheeled hopper fastened to the front of tractor or the rear of a haul truck), the cold mix is dumped into a hopper and falls directly on the road where it is spread and struck off to the required thickness.

The same equipment and techniques used to compact and cure conventional cold mix asphalt pavements are applicable to recycled cold mix.

Quality Control

To ensure the consistency and quality of a recycled cold plant mix, quality control of the RAP is essential. Random samples of the RAP or recycled material should be analyzed for aggregate gradation, asphalt cement content, and moisture content. The recycled material must be closely inspected to make sure that the RAP is consistent in size and appearance and that subgrade soil (or other possible contaminants) have not been included in the RAP.

Plant operations should be monitored to ensure that the proper amount of emulsified or foamed asphalt is being added and that the moisture content of the recycled mix is in the proper range for maximum compaction at the project site. The amount of any additional aggregate being mixed with the RAP should also be monitored. Loose samples of the recycled mix should be obtained and extraction tests performed to monitor mix gradation and asphalt content, as well as moisture content. Mixes should be sampled in accordance with AASHTO T168.(22)

Achieving the proper compaction or densification of the paving material is essential to proper performance. A test strip should be used at the start of the project to establish a target density and number of roller passes needed to achieve that density. The in-place density of the cold mix paving material can then be monitored by using a nuclear density gauge in accordance with ASTM D2950.(23)

Cold In-Place Recycling

Mixing, Placing and Compacting

A typical CIPR train consists of a cold milling machine (with water added as necessary for cooling and dust control) that is capable of reclaiming the old asphalt pavement to depths from about 100 mm (4 in) to 150 mm (6 in). CIPR plants consist of a screening and sizing or crushing unit, as well as a mixing unit for the addition of polymer-modified high-float emulsion, as determined by the mix design, and also water, if required. Mixing may be accomplished using a motor grader blade, a rotary pulvimixer, a windrow type mixer, or a traveling plant pugmill, which offers the highest degree of grading control.(24) A reclaim/paver unit is also part of the system to place the recycled cold mix. The mixing and placement units are combined in some trains in what are referred to as mixer-pavers. Care must be taken during the CIPR operation to avoid the incorporation of the granular base material into the mixer.

After about 30 minutes of curing and drying, the material is compacted with a large rubber-tired roller, followed by a vibratory steel drum roller. Compaction of CIPR paving mixtures is normally accomplished at a moisture content of less than 2 percent at a minimum of 97 percent of laboratory maximum density.

Curing

Following about 2 weeks of additional curing during favorable weather conditions, preferably at temperatures at or in excess of 16°C (60°F), a hot mix asphalt overlay is generally applied.

Quality Control

As with HIPR, the crucial step in the quality control of CIPR mixes is in the initial process of project selection. If an existing pavement exhibits distress resulting from a subgrade or base failure, it cannot be remedied simply by recycling the surface layer. Pavements that have been rutted, heavily patched, or chip-sealed are not good candidates for CIPR projects. Also, core specimens of the pavement being considered for CIPR should be taken and examined for variations in pavement layers, delaminations, and saturated material adjacent to voids or delaminations.

To ensure the success of a CIPR mix, quality control of the RAP is essential. Random samples of the RAP or recycled material should be analyzed for aggregate gradation, asphalt content, and moisture content. The recycled material must be closely inspected to make sure that the RAP is consistent in size and appearance and that subgrade soil (or other possible contaminants) have not been included in the RAP.

Field quality control measures during CIPR operations include monitoring the depth of scarification, the coating of the aggregate by the emulsion, the proper curing of the emulsion, the visual appearance and possible segregation of the recycled material, the compaction procedure, and appearance of the recycled pavement surface after compaction. Loose samples of the recycled mix should be obtained and extraction tests performed to monitor mix gradation and emulsion content, as well as moisture content. The moisture content of recycled pavement should be less than 1 percent of the existing pavement prior to recycling.(25)

Achieving the proper compaction or densification of the recycled paving material is essential to proper performance. The in-place density of the recycled mix should be monitored by using a nuclear density gauge in accordance with ASTM D2950.(23)

UNRESOLVED ISSUES

While cold asphalt pavement recycling technologies are well established, there is still a need for additional performance information, particularly with regard to creep (rutting resistance), fatigue endurance, and durability. In addition, there is a need to assess whether RAP can be used in wearing surface cold mixes. Further investigation is also needed to evaluate the ability of cold recycled plant mixes to perform on higher traffic volume roadways. There is also a need for more correlation of field and laboratory measurements to refine guidelines for laboratory prediction of field performance, including, for instance, laboratory curing procedures that best simulate field conditions.

Some specific issues that require resolution include:

- further information on the variability of RAP, especially from blended stockpiles;
- a consensus regarding mix design and testing procedures for plant recycled cold mix and CIPR asphalt mixtures;
- the suitability of CIPR for use with surface treatments and/or rubberized paving materials;
- a more accurate determination of the structural layer coefficient for plant recycled cold mix and CIPR asphalt mixtures; and
- an environmental evaluation of any potentially harmful impacts from cold mix plant recycling and/or cold in-place recycling.

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INTRODUCTION

Reclaimed asphalt pavement (RAP) can be used as granular base or subbase material in virtually all pavement types, including paved and unpaved roadways, parking areas, bicycle paths, gravel road rehabilitation, shoulders, residential driveways, trench backfill, engineered fill, pipe bedding, and culvert backfill.(1,2)

Although the use of RAP in granular base applications does not recover the asphalt cement potential in the old pavement, it does provide an alternate application where no other markets (asphalt paving) are available or where unsuitable material (such as soil or mud) may have been combined with the RAP so that it cannot be used as part of a recycled pavement.

PERFORMANCE RECORD

RAP that has been properly processed and in most cases blended with conventional aggregates has demonstrated satisfactory performance as granular road base for more than 20 years and is now considered standard practice in many areas. At least 13 state agencies (Arizona, Illinois, Louisiana, Maine, Nebraska, New Hampshire, North Dakota, Oregon, Rhode Island, South Dakota, Texas, Virginia, and Wisconsin) have used RAP as aggregate in base course. At least four state agencies (Alaska, New York, Ohio, and Utah) have used RAP as unbound aggregate in subbase, and at least two states (California and Vermont) have experience with RAP use in stabilized base course.(3)

In addition to the states listed above, it has also been reported that RAP has been used as a base course additive in Idaho and New Mexico, and as a subbase additive in at least 10 other states, including Connecticut, Georgia, Iowa, Kansas, Massachusetts, Minnesota, Montana, Oklahoma, Tennessee, and Wyoming.(4) It has further been reported that Kentucky has had some limited experience with the use of RAP in roadbase, although no information is available concerning its performance.(5)

Overall, the performance of RAP as a granular base or subbase aggregate, or as an additive to granular base or subbase, has been described as satisfactory, good, very good, or excellent.(3,4) Some of the positive features of RAP aggregates that have been properly incorporated into granular base applications include adequate bearing capacity, good drainage characteristics, and very good durability. However, RAP that is not properly processed or blended to design specification requirements may result in poor pavement performance. Increasing the RAP content results in a decrease in the bearing capacity of the granular base. In addition, where conventional granular material has been placed over processed RAP (and not homogeneously blended), the coarse granular material (sometimes referred to as float material) tends to ravel under traffic.(6)

MATERIAL PROCESSING REQUIREMENTS

Crushing and Screening

Stockpiled RAP must be processed to the desired aggregate gradation using conventional equipment consisting of a primary crusher, screening units, secondary crusher (optional), conveyors, and a stacker.

Blending

To avoid agglomeration of crushed RAP, it should be blended as soon as possible with conventional aggregate (using a cold feed system) to a homogeneous mixture. However, blended material that is stockpiled for a considerable period of time, particularly in warm weather, may harden and require recrushing and rescreening before it can be incorporated into granular base applications.

Stockpiling

Blended RAP-aggregate stockpiles should not be allowed to remain in place for extended time periods in most climates because the stockpiled material is likely to become overly wet, possibly requiring some drying prior to use.

Placement by In-Place Processing

In-place processing consists of self-propelled pulverizing units that break up and crush the existing asphalt concrete, (typically up to a depth of about 100 mm (4 in)) and underlying granular material to a total maximum depth of 200 mm (8 in) and thoroughly mix the materials in place. The depth of processing must be closely monitored since cutting too deep can incorporate subbase material while cutting too shallow increases the percentage of RAP in the blend.

ENGINEERING PROPERTIES

Some of the engineering properties of RAP that are of particular interest when RAP is used in granular base applications include gradation, bearing strength, compacted density, moisture content, permeability, and durability.

Gradation: The gradation for milled RAP is governed by the spacing of the teeth and speed of the pulverizing unit. Wider tooth spacing and higher speed result in larger particle sizes and coarser gradation. RAP can be readily processed to satisfy gradation requirements for granular base and subbase specifications, such as AASHTO M147.(7)

Bearing Strength: The bearing capacity of blended RAP is strongly dependent on the proportion of RAP to conventional aggregate. The bearing capacity decreases with increasing RAP content. The California Bearing Ratio (CBR) is reduced below that expected for conventional granular base when the amount of RAP exceeds 20 to 25 percent.(8) CBR values have been shown to decrease almost directly with increasing RAP contents.(6)

Compacted Density: Due to the coating of asphalt cement on RAP aggregate, which inhibits compaction, the compacted density of blended granular material tends to decrease with increasing RAP content.(6)

Moisture Content: The optimum moisture content for RAP blended aggregates is reported to be higher than for conventional granular material, particularly for RAP from pulverizing operations, due to a higher fines content and the absorptive capacity of these fines.(8)

Permeability: The permeability of blended granular material containing RAP is similar to conventional granular base course material.(8)

Durability: Since the quality of virgin aggregates used in asphalt concrete usually exceeds the requirements for granular aggregates, there are generally no durability concerns regarding the use of RAP in granular base, especially if the RAP is less than 20 to 25 percent of the base.

DESIGN CONSIDERATIONS

The key design parameter for incorporating processed RAP into granular base material is the blending ratio of RAP to conventional aggregate that is needed to provide adequate bearing capacity. The ratio can be determined from laboratory testing of RAP aggregate blends using the

CBR test method(9) or previous experience. It has been reported that blends of up to 30 percent asphalt-coated particles from RAP have been incorporated into blended granular base material.(10)

The presence of asphalt cement in the RAP, however, does have a significant strengthening effect with time. It has been reported that specimens with 40 percent RAP blended in granular base material have produced CBR values exceeding 150 percent after 1 week.(8) RAP produced by grinding or pulverizing has a lower bearing capacity than crushed RAP, due to the higher generation of fines.(11) As a result, for use in load-bearing applications, granular RAP is usually blended with conventional aggregates.

Conventional AASHTO pavement structural design procedures can be employed for granular base containing reclaimed asphalt pavement. The AASHTO Design Guide(12) is recommended for the thickness design of base course or subbase layers that contain RAP as a percentage of, or possibly even all of, the base or subbase. If the RAP is only a portion of the base or subbase material (less than 30 percent), the structural layer coefficient normally recommended for granular base materials (0.11 to 0.14) can be used. If the RAP constitutes a greater percentage, or even all, of the base or subbase material, some adjustment of the structural layer coefficient may be considered.

CONSTRUCTION PROCEDURES

Material Handling and Storage

Essentially the same equipment and procedures used to stockpile, handle, and place conventional aggregates in granular base are applicable to blended granular material containing RAP. For major projects where control of engineering properties is critical, controlled blending of the RAP with conventional granular material at a central plant provides better consistency than the product of in-place, full-depth processing.

Since each source of RAP will be different, random sampling and testing of the RAP stockpile must be performed to quantify and qualify the RAP. Samples of the stockpiled RAP should be used to determine the optimum blend of materials.(13) Additional care is required during stockpiling and handling to avoid segregation or re-agglomerating.

Placing and Compacting

Recycled asphalt pavement, which is recovered, crushed, screened, and blended with conventional aggregates, is placed as conventional granular material. Alternatively, in-place processing, which involves pulverizing the existing pavement and thoroughly mixing the individual surface and granular base course layers into a relatively homogeneous mixture and recompacting it as granular base, can also be used.

Conventional granular aggregates do not bond well with RAP or blended granular material containing RAP. Consequently, raveling can occur if thin layers of conventional aggregates are placed over material containing RAP.

During placement, finish grading can be difficult because of the adhesion of asphalt in the RAP. Particular attention should be paid to obtaining adequate compaction to avoid postconstruction densification of granular base materials containing RAP.

Both blended granular material and pulverized material can be similarly compacted using conventional compaction equipment. It has been reported that compaction is improved if little or no water is used.(6)

Quality Control

The same test procedures used for conventional aggregate are appropriate for granular base/subbase containing RAP. The same field test procedures used for conventional aggregate are recommended for granular base applications when using RAP. Standard laboratory and field test methods for compacted density are given by AASHTO T191,(14) T205,(15) T238,(16) and T239.(17)

Testing of moisture content and compaction using nuclear gauges is affected by the presence of RAP. Both parameters tend to be overestimated because of the presence of hydrogen ions in the asphalt cement contributing to the total count. To avoid this problem, compaction of granular base containing RAP may be carried out using a control strip.(6) Laboratory moisture checks should be completed to calibrate nuclear density gauge moisture content readings.

UNRESOLVED ISSUES

There is a need to establish standard specifications for the incorporation of RAP into granular base and standard methods for determining in-place compacted density.

In addition, there is a need to resolve some environmental concerns regarding leachability characteristics for RAP, as well as various RAP-aggregate blends, in order to develop procedures for the stockpiling and placing of base or subbase materials containing RAP in situations where there may be groundwater contact.

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INTRODUCTION

In addition to recycling into asphalt paving or incorporation into bases or subbases, some reclaimed asphalt pavement (RAP) has been used for embankment construction. It can also be used as a fill material. When used as an embankment or fill material, the undersize portion of crushed and screened RAP, typically less than 50 mm (2 in), may be blended with soil and/or finely graded aggregate. Uncrushed or more coarsely graded RAP may be used as the embankment base.

Although the use of RAP in embankment construction does not take any advantage of the asphalt cement component, it does, nevertheless, provide an alternate application where no other markets for reuse are readily available, or where the RAP may be unsuitable for use in asphalt concrete pavement. The properties of RAP are largely dependent on the properties of the constituent materials and asphalt concrete type used in the old pavement.(1,2)

PERFORMANCE RECORD

Although use of RAP as an embankment construction material does not appear to be extensive, it has been reported that at least nine states have made some use of RAP for this purpose. States that have made use of RAP as an additive in embankment construction include Connecticut, Indiana, Kansas, Montana, New York, and Tennessee. States that have used RAP directly as an embankment base material include California, Connecticut, Illinois, Louisiana, and Tennessee.(3) The performance of RAP in these applications was generally considered to be satisfactory to good.

MATERIAL PROCESSING REQUIREMENTS

Crushing

Processing requirements for embankment or fill applications are minimal. Primary crushing may be necessary to satisfy gradation requirements. However, some jurisdictions permit the use of broken pieces of old asphalt pavement, provided the specified maximum size (similar to boulders) is not exceeded.

Blending

Crushed RAP is sometimes mixed with conventional earth fill materials or crushed aggregates and used in embankment construction.

ENGINEERING PROPERTIES

Some of the engineering properties of RAP that are of particular interest when RAP is used in embankment applications include gradation, compacted density, moisture content, shear strength, consolidation characteristics, permeability, durability, drainage characteristics, bearing strength, and corrosivity.

Gradation: The gradation of RAP is controlled by crushing and screening. The gradation and physical requirements of AASHTO M145(4) are usually readily satisfied by RAP or blends of RAP and soil or crushed aggregate. If used as an embankment base material, the maximum particle size of RAP will probably be less than 600 mm (24 in).

Compacted Density: Due to its asphalt cement content, the compacted unit weight of RAP (1600 to 2000 kg/m^3 (100 to 125 lbs/ft^3)) is likely to be somewhat lower than that of earth or rock.(5) The finer the RAP is crushed and sized, the higher its compacted density.

Moisture Content: The optimum moisture content for RAP-aggregate blends is reported to be higher than for conventional embankment material, particularly for RAP from pulverizing operations, due to higher fines generation.(6)

Shear Strength: The shear strength of RAP that has been crushed and sized will be based on internal friction, with little or no cohesion, and should be comparable to that of a similarly graded natural aggregate. RAP-aggregate blends should also have an internal friction angle in the same range as the natural aggregate. The shear strength of RAP-soil blends will likely be based mainly on internal friction, with little or no cohesion, and will be dependent on the relative proportions of the RAP and the soil.

Consolidation Characteristics: The compressibility or consolidation characteristics of RAP-soil blends will probably be within the range of a granular soil, depending on the gradation, moisture content, and proportion of soil added to the RAP. For coarsely graded RAP, or RAP-aggregate blends, the potential for compressibility should, for all practical purposes, be negligible.

Permeability: The permeability of blended RAP is similar to that of conventional granular material or soil-aggregate blends having similar gradation.(6)

Durability: Since the quality of virgin aggregates used in asphalt concrete usually exceeds the requirements for embankment/fill material, there are generally no durability concerns regarding the use of RAP in this application.

Drainage Characteristics: RAP is nonplastic, free draining, is not frost susceptible, and can be blended and compacted with other suitable fill materials.

Bearing Strength: The bearing strength of an embankment is mainly of importance only in the top 1 meter (3 ft), which is the portion of the embankment that provides the subgrade support for the pavement structure. The bearing strength of subgrade materials is usually determined by the California Bearing Ratio (CBR) test. The CBR value for RAP should be comparable to that of crushed stone of a similar gradation. The CBR of RAP-soil blends should be comparable to that of a well-graded granular soil. The top portion of an embankment will normally consist of soillike materials, with the coarser materials (crushed stone or rock) in the lower portions of the embankment.

Corrosivity: On the basis of limited testing results, RAP is considered noncorrosive.(7,8)

DESIGN CONSIDERATIONS

The design requirements for RAP in embankment construction are the same as for similar sized soil-aggregate blends, conventional aggregates, or shot rock fill. Where pieces of broken asphalt pavement are used as embankment base, size and placement restrictions should apply in the same manner as for boulders and cobbles. It is recommended that such uncrushed materials not be placed where they may have an impact on future construction activities. Some jurisdictions require that a minimum separation be maintained between watercourses and fill materials containing RAP to avoid submersion of RAP in water, which may or may not be a potential environmental concern.(9)

Design procedures for embankments or fill containing RAP are the same as design procedures for conventional embankment materials. The design should take into consideration slope stability, settlement or consolidation, and bearing capacity concerns. If the embankment is to be constructed using a blend of RAP with soil and/or crushed aggregate, a representative sample of the blended material should be tested, if possible, for triaxial compression(10) and California

Bearing Ratio (CBR).(11) The maximum particle size for the triaxial test is 5 mm (No. 4 sieve). The maximum particle size for the CBR test is 19 mm (3/4 in sieve).

CONSTRUCTION PROCEDURES

Material Handling and Storage

The same methods and equipment used to store or stockpile conventional aggregates are applicable for reclaimed asphalt pavement.

Since each source of RAP will be different, random sampling and testing of the RAP stockpile must be performed to quantify and qualify the RAP. Representative samples of the stockpiled RAP should be used in the optimum blend design.(2) Additional care is required during stockpiling and handling to avoid segregation or re-agglomeration.

Placing and Compacting

The same methods and equipment for compacting conventional fill can be used for compacting crushed RAP or blends of soil and RAP. It is reported that granular materials containing RAP appear to compact better if little or no water is used.(5) Where large, broken pieces of old asphalt pavement are incorporated in embankment construction, additional attention is needed during compaction to ensure that no large voids are formed within the fill that could contribute to subsequent long-term differential settlement. Standard laboratory and field test methods for compacted density are given by AASHTO T191,(12) T205,(13) T238,(14) and T239.(15)

Quality Control

The same field test procedures used for conventional soils or crushed aggregate materials are also appropriate for RAP, or blends of RAP and soils or crushed aggregates.

When RAP is used for construction of an embankment base or foundation material, compaction operations must be visually inspected on a continuous basis to ensure that the specified degree of compaction can be achieved, or that there is no movement under the action of compaction equipment. The construction of embankment bases or foundations containing rock or oversize materials usually requires a method specification, in which the procedures and type of equipment for placement and compaction are stipulated, but no testing methods or acceptance criteria are indicated.

UNRESOLVED ISSUES

Although RAP is not frequently incorporated into embankments, there is a need to establish standard specifications for the use of RAP in embankment construction, either by itself as an embankment base material, or blended with soil and/or crushed aggregate.

Although the available body of technical data indicate that RAP is a nonleachable material, there is a need to develop a procedure for stockpiling and placing of fill materials containing RAP in situations where there may be groundwater contact or concerns about runoff quality.

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ORIGIN

Reclaimed concrete material (RCM) is sometimes referred to as recycled concrete pavement (RCP), or crushed concrete. It consists of high-quality, well-graded aggregates (usually mineral aggregates), bonded by a hardened cementitious paste. The aggregates comprise approximately 60 to 75 percent of the total volume of concrete.

RCM is generated through the demolition of Portland cement concrete elements of roads, runways, and structures during road reconstruction, utility excavations, or demolition operations. In many metropolitan areas, the RCM source is from existing Portland cement concrete curb, sidewalk and driveway sections that may or may not be lightly reinforced. The RCM is usually removed with a backhoe or payloader and is loaded into dump trucks for removal from the site. The RCM excavation may include 10 to 30 percent subbase soil material and asphalt pavement. Therefore, the RCM is not pure Portland cement concrete, but a mixture of concrete, soil, and small quantities of bituminous concrete.

The excavated concrete that will be recycled is typically hauled to a central facility for stockpiling and processing or, in some cases (such as large reconstruction projects), processed on site using a mobile plant. At the central processing facility, crushing, screening, and ferrous metal recovery operations occur. Present crushing systems, with magnetic separators, are capable of removing reinforcing steel without much difficulty. Welded wire mesh reinforcement, however, may be difficult or impossible to remove effectively.

CURRENT MANAGEMENT OPTIONS

Recycling

Reclaimed concrete material can be used as an aggregate for cement-treated or lean concrete bases, a concrete aggregate, an aggregate for flowable fill, or an asphalt concrete aggregate. It can also be used as a bulk fill material on land or water, as a shore line protection material (rip rap), a gabion basket fill, or a granular aggregate for base and trench backfill.

Disposal

Disposal in landfills, near the right-of-way, and in borrow pits or depleted quarries has historically been the most common method of managing RCM. However, recycling has become a more attractive option, particularly in aggregate-scarce areas and in large urban areas where gathering and distribution networks for RCM have been developed.

MARKET SOURCES

Recycled concrete material can usually be obtained from central processing plants where the processed material is stockpiled and sold. Well-processed RCM will normally yield consistent physical properties , but RCM properties can sometimes vary depending on the properties of the quality of the recovered concrete.

Variations between concrete types result from differences in aggregate quality, aggregate size, concrete compressive strength, and uniformity.(1) For instance, aggregates in concrete not exposed to severe weathering (such as footings and covered structural members) can contain a higher proportion of deleterious substances than those in pavement concrete. Precast concrete generally has smaller aggregate size, higher compressive strength, and less variation in strength and other properties than cast-in-place concrete. Some recycled pavements may show evidence of distress from alkali-silica reaction due to the presence of a siliceous aggregate with reactive constituents. In areas where deicing salts are extensively used, recycled concrete may contain relatively high levels of chlorides.

HIGHWAY USES AND PROCESSING REQUIREMENTS

Aggregate Substitute

The use of RCM as an aggregate substitute in pavement construction is well established, and includes its use in granular and stabilized base, engineered fill, and Portland cement concrete pavement applications. Other potential applications include its use as an aggregate in flowable fill, hot mix asphalt concrete, and surface treatments.

To be used as an aggregate, RCM must be processed to remove as much foreign debris and reinforcing steel as possible. Reinforcing steel is sometimes removed before loading and hauling to a central processing plant. Most processing plants have a primary and secondary crusher. The primary crusher (e.g., jaw crusher) breaks the reinforcing steel from the concrete and reduces the concrete rubble to a maximum size of 75 mm (3 in) to 100 mm (4 in). As the material is conveyed to the secondary crusher, steel is typically removed by an electromagnetic separator. Secondary crushing further breaks down the RCM, which is then screened to the desired gradation. To avoid inadvertent segregation of particle sizes, coarse and fine RCM aggregates are typically stockpiled separately.

MATERIAL PROPERTIES

Physical Properties

Processed RCM, which is 100 percent crushed material, is highly angular in shape. Due to the adhesion of mortar to the aggregates incorporated in the concrete, processed RCM has rougher surface texture, lower specific gravity, and higher water absorption than comparatively sized virgin aggregates. As processed RCM particle size decreases, there is a corresponding decrease in specific gravity and increase in absorption, due to the higher mortar proportion adhering to finer aggregates. High absorption is particularly noticeable in crushed fine material, which is less than 4.75 mm in size (minus No. 4 sieve size), and particularly in material from air-entrained concrete (since there is substantially more air-entrained mortar in the fine than the coarse RCM aggregates). The minus 0.075 mm (No. 200 sieve) fraction is usually minimal in the RCM product. Some typical physical properties of processed RCM are listed in Table 14-1.

Processed RCM is generally more permeable than natural sand, gravel, and crushed limestone products.(2)

Table 14-1. Typical physical properties of processed reclaimed concrete material.(3)

Property	Value
Specific Gravity	
- Coarse particles	2.2 to 2.5
- Fine particles	2.0 to 2.3
Absorption, %	
- Coarse particles	2 to 6
- Fine particles	4 to 8(a)
a. Absorption values as high as 11.8 percent have been reported.(1)	

Chemical Properties

The cement paste component of RCM has a substantial influence on RCM alkalinity. Cement paste consists of a series of calcium-aluminum-silicate compounds, including calcium hydroxide, which is highly alkaline. The pH of RCM-water mixtures often exceeds 11.

RCM may be contaminated with chloride ions from the application of deicing salts to roadway surfaces or with sulfates from contact with sulfate-rich soils. Chloride ions are associated with corrosion of steel, while sulfate reactions lead to expansive disintegration of cement paste. RCM may also contain aggregate susceptible to alkali-silica reactions (ASR). When incorporated in concrete, ASR-susceptible aggregates may cause expansion and cracking.

The high alkalinity of RCM (pH greater than 11) can result in corrosion of aluminum or galvanized steel pipes in direct contact with RCM and in the presence of moisture. Similarly, RCM that is highly contaminated with chloride ions can lead to corrosion of steel.

Mechanical Properties

Processed coarse RCM, which is greater than 4.75 mm in size (No. 4 sieve size), has favorable mechanical properties for aggregate use, including good abrasion resistance, good soundness characteristics, and bearing strength. Typical mechanical properties are given in Table 14-2.

Table 14-2. Typical mechanical properties of reclaimed concrete material.

Property	Value
Los Angeles Abrasion Loss (ASTM C131), (%) - Coarse particles	20-45(2,3)
Magnesium Sulfate Soundness Loss (ASTM C88), (%) - Coarse particles - Fine particles	 4 or less(2,3,4) less than 9(1)
California Bearing Ratio (CBR),(%)*	94 to 148(3,4)
* Typical CBR value for crushed limestone is 100 percent.	

Los Angeles Abrasion loss values are somewhat higher than those of high-quality conventional aggregates. Magnesium sulfate soundness and California Bearing Ratio (CBR) values are comparable to conventional aggregates.

The results of a 6-year Long Island, New York, study of materials processed from uncontrolled stockpiles for use as a granular subbase or base, presented in Table 14-3, reveal that physical properties such as magnesium sulfate soundness, Los Angeles Abrasion, density, and CBR of processed RCM are very consistent and can be expected to fall within a predictable range of values.(5)

Table 14-3. 6-year study of RCM from uncontrolled stockpiles on Long Island, NY(5)

Physical Property	Test Results		
	Mean	Std. Dev.	Tests Performed
Magnesium Soundness (%)	3.8	1.3	107
Los Angeles Abrasion (%)	36.5	3.6	112
Dry Density (lb/ft^{2})	129.0	2.6	143
CBR (%)	148.0	28.7	157

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RECLAIMED CONCRETE MATERIAL

User Guideline

Portland Cement Concrete

INTRODUCTION

Reclaimed concrete material (RCM) can be used as coarse and/or fine aggregate in Portland cement concrete (PCC) pavements. However, concrete incorporating more than about 10 to 20 percent fine RCM aggregates can suffer a reduction in quality because of the high amount of water required to maintain adequate workability of the concrete mix.

PERFORMANCE RECORD

RCM has been accepted by many jurisdictions and is covered by conventional aggregate specifications and by several highway agency specifications, including those in Colorado, Connecticut, Illinois, Indiana (special provisions), Iowa, Louisiana, Michigan, Montana, North Dakota, Oklahoma, and Wyoming.(1) For large projects and/or projects where suitable quality aggregate is not readily available, site-processed RCM can be significantly cheaper than new aggregate hauled to the site.

MATERIAL PROCESSING REQUIREMENTS

Material Handling

When RCM is collected from different sources or types of concrete, it should either be blended with other aggregates or separately processed and placed in separate stockpiles to ensure uniformity of RCM aggregate properties.

Crushing and Screening

Crushing and screening is required to produce aggregate within the limits for concrete mix gradation.

Quality Control

Levels of impurities such as sulfate and chloride ions, alkali-reactive aggregate and freeze-thaw susceptible aggregate (which can lead to D-cracking in concrete pavements) must be controlled to ensure that the finished concrete has consistent strength and durability.(2,3) D-cracks are closely spaced cracks parallel to transverse and longitudinal joints that multiply outward to the center of the pavement panel. These cracks typically start in the saturated aggregate at the base of the pavement and progress upward. It has been recommended that the degree of contamination and potential reactivity of RCM aggregates should not exceed the limits permitted for virgin aggregates.(4)

ENGINEERING PROPERTIES

Some of the engineering properties that are of particular interest when RCM is used in Portland cement concrete applications include gradation, particle shape, specific gravity, absorption, moisture content, durability, and permeability.

Gradation: Recycled concrete material should be crushed and screened to produce aggregate that satisfies the AASHTO M6(5) and M80(6) gradation requirements for PCC. With appropriate adjustments, a plant can produce any desired gradation. Crushed fine aggregates (minus 4.75 mm (No.4 sieve)) are generally not used or are blended with natural sand.

Shape: Processed RCM, being 100 percent crushed material, is highly angular in shape. While this shape assists in increasing the strength of the mix, it can reduce its workability.

Specific Gravity: The specific gravity of processed coarse RCM aggregate ranges from 2.0 to 2.5, which is slightly lower than that of virgin aggregates. This is primarily due to the adhesion of mortar to virgin aggregate particles. The differences become more pronounced with decreasing particle size. The specific gravity of processed RCM fines is in the range of 2.0 to 2.3.(7)

Absorption: RCM aggregates can be expected to have higher absorption values than virgin aggregates. High absorption is particularly noticeable in crushed fine material (minus 4.75 mm (No.4) sieve) from air-entrained concrete. Absorption values for fine-grained RCM generally range from 4 to 8 percent (compared with 2 percent or less for fine virgin concrete aggregates).(7) If not accounted for in mix design, higher absorption values could adversely impact concrete workability.

Moisture Content: The in-situ stockpile moisture content for processed RCM is typically the same as that for conventional granular material.

Durability: Coarse-grained RCM typically exhibits good soundness characteristics and abrasion resistance. Durability and soundness properties of processed RCM are similar to those of the virgin aggregates incorporated in the concrete and generally satisfy specification requirements for concrete aggregates.(2)

Permeability: Coarse-grained RCM is free draining (more permeable than conventional granular material due to lower fines content).

Some of the properties of concrete mixes containing RCM that are of interest include strength characteristics, workability, resistance to freeze-thaw, deleterious substances, alkali-aggregate reactivity, and corrosivity.

Strength Characteristics: In RCM mixes, compressive strength can be reduced up to 25 percent compared to mixes with conventional aggregates, with up to 30 percent improvement in the damping capacity, and higher amounts of drying shrinkage and creep.(8) For a given compressive strength (at 28 days), both the static and dynamic moduli of elasticity for recycled-aggregate concrete are significantly lower (up to 40 percent) than those for concrete containing virgin aggregate.(9,10) Concrete mixes incorporating coarse RCM aggregates generally can be expected to develop about 10 percent lower flexural strength at equal water/cement ratio and slump than conventional aggregates.

Workability: If fine RCM aggregates are used, concrete workability decreases (due to the high absorption and angularity of crushed RCM fines) and concrete flexural strength is reduced about 10 to 20 percent.(11)

Resistance to Freeze-Thaw: Concrete incorporating RCM aggregates has good resistance to freeze-thaw exposure provided a suitable air void system is present in the mortar phase of the concrete containing RCM aggregate.

Deleterious Substances: Chlorides may be present in RCM as a result of many years of deicing salt application on an old pavement. High levels of chloride in the recycled aggregate can induce corrosion of reinforcing steel embedded in a new concrete. However, the quantity of chloride typically found in old concrete pavement is below critical threshold values.(12) A threshold value of 2.4 kg/m^3 (4 lbs/yd^3) is recommended by the American Concrete Pavement Association as a threshold to trigger the removal and replacement of concrete bridge decks due to corrosion potential.(7,13)

Recycled concrete material may also contain coarse and/or fine aggregates that are susceptible to alkali-silica reaction.(9,13)

DESIGN CONSIDERATIONS

Mix Design

Crushed RCM is considered a conventional coarse aggregate for Portland cement concrete mixtures by AASHTO M80. Coarse aggregates should conform to the grading requirements outlined in AASHTO M43(14) for the grading specified. AASHTO M6 provides the physical properties and grading requirements for concrete fine aggregate.(15)

Prior to use, trial batches should be prepared according to ACI 211 procedures(16) and necessary mix adjustments made to ensure that the specified requirements are attained.

Special care is required when incorporating RCM fines to avoid dramatic reductions in concrete workability, strength, and finishability. Blending RCM fines with natural sand at substitution rates of 10 to 20 percent has resulted in satisfactory performance. Several trial mixes are often required to generate sufficient data to identify the optimum substitution rate.

Due to their high absorption, prewetting of RCM aggregates is important. Aggregates that are not saturated will absorb water from the concrete mix.

In addition to satisfying the requirements of AASHTO M43 and M6, consideration must be given to sulfate and chloride contamination of RCM aggregates. Chloride contamination is often due to the application of deicing salts (on pavements and sidewalks). High concentrations of chloride ions can result in corrosion of reinforcing steel. ACI 201.2R, "Guide to Durable Concrete,"(17) provides guidance on the limits of such contaminants for various service conditions.

Where sulfate attack is of concern, the potential for deterioration should be evaluated by the ASTM C452 sulfate expansion test.(18) Sulfate-resistant cement such as Type II or V can be used, if necessary.

Where alkali-silica reactivity is of concern, the potential for deterioration should be evaluated by the ASTM C289 test.(19) Low-alkali cement can be used if necessary.

For reinforced concrete pavement construction or plain jointed pavements without load transfer dowels, it is important to ensure that the top size coarse aggregate is sufficiently large (typically 40 mm) to provide adequate interlock across joints and cracks.

Structural Design

Conventional AASHTO rigid pavement thickness design procedures are appropriate for rigid pavements incorporating RCM.

CONSTRUCTION PROCEDURES

The same equipment and procedures used for concrete containing conventional aggregate may be used to batch, mix, transport, place, and finish concrete containing processed RCM aggregates. However, additional care and some minor changes are necessary to avoid potential problems.

Material Handling and Storage

The same methods and equipment used to store or stockpile conventional aggregates are applicable for RCM.

It is important to monitor the moisture content of RCM aggregates in stockpiles to permit determinations of the mix water requirements. Sprinkling stockpiles to keep RCM aggregates saturated is an effective method of minimizing their potential to absorb moisture from the concrete mix.

Mixing, Placing, and Compacting

The same methods and equipment can be used to mix, place, and compact RCM concrete mixes and conventional concrete mixes.

Slipforming and finishing concrete made with RCM aggregates is improved by reducing or eliminating the RCM fines content in favor of natural sand.

Quality Control

The same quality-control procedures for conventional Portland cement concrete pavement are required for Portland cement concrete incorporating RCM aggregates. The slump, air content, and temperature of the plastic concrete should be monitored at the time of placement, and compressive strength cylinders cast for compressive strength determinations in accordance with the ASTM C39(20) procedure. Flexural strength can be determined using flexural strength prisms (ASTM C78)(21) or by splitting tensile tests (ASTM C496)(22) on cylinders. Due to the sensitivity of concrete pavement performance and durability to water-cement ratio, and the potential variability in RCM gradation, specific gravity, and absorption, particular attention should be given to these aggregate properties when using RCM in concrete pavement mixtures, and appropriate adjustments to the quantity of mixing water completed during concrete production.

UNRESOLVED ISSUES

There is a need to obtain long-term performance and life-cycle cost data for concrete made with processed RCM aggregates to assess its durability, performance, and expected service life.

Limits on chloride and sulfate contents of concrete materials are well established. However, further investigation concerning the effect of other impurities that RCM may contain (other than chloride and sulfate) such as wood, asphalt, and earth on concrete performance is needed. Also, there is a need for guidance regarding the monitoring and restriction of impurities in RCM.

Further, there is a need to determine whether alkali-silica reactive or D-cracked concrete can be recycled as aggregate and to develop appropriate specifications for the use of such materials.

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INTRODUCTION

Reclaimed concrete material (RCM) can be used as coarse and/or fine aggregate in granular base. The properties of processed RCM generally exceed the minimum requirements for conventional granular aggregates. Being a 100 percent crushed material, processed RCM aggregates "lock up" well in granular base applications, providing good load transfer when placed on weaker subgrade. The lower compacted unit weight of RCM aggregates compared with conventional mineral aggregates results in higher yield (greater volume for the same weight), and is therefore economically attractive to contractors. For large reconstruction projects, on-site processing and recycling of RCM are likely to result in economic benefits through reduced aggregate hauling costs.

PERFORMANCE RECORD

RCM that has been properly processed and tested for appropriate specification compliance has been widely used and has generally demonstrated satisfactory performance in granular base applications. The use of processed RCM as aggregate in base or subbase applications has been accepted by many jurisdictions. Twenty states presently use RCM. They include Arizona, California, Colorado, Florida, Indiana, Iowa, Louisiana, Maryland, Massachusetts, Minnesota, Missouri, Nebraska, New Jersey, New York, North Dakota, Ohio, Pennsylvania, Rhode Island, South Carolina, and Texas.

Two highway agencies (Illinois and Pennsylvania) have specifications that directly address RCM use in granular base.(1) A number of states are conducting or have proposed research into the use of RCM as aggregate for granular base course. They include Arizona, Iowa, Louisiana, Michigan, Missouri, and Nebraska.

Some of the positive features of RCM aggregates in granular base applications include the ability to stabilize wet, soft, underlying soils at early construction stages, good durability, good bearing strength, and good drainage characteristics.

There is recent evidence that the use of some unsuitable or improperly processed RCM aggregate can adversely affect pavement subdrainage systems and pavement performance.(2) Tufa-like (white, powdery precipitate) precipitates have been reported by a number of agencies to have clogged subdrains and blinded geotextile filters.(2) The tufa precipitate appears to be Portlandite from unhydrated cement and/or calcium carbonate ($CaCO_3$), formed by the chemical reaction of atmospheric carbon dioxide with the free lime (CaO) in the RCM. However, the problem is not universal, and many pavements with RCM granular base are reported to be functioning satisfactorily without any apparent tufa formation.

MATERIAL PROCESSING REQUIREMENTS

Crushing and Screening

Following the initial crushing of concrete rubble in a jaw crusher and removal of any steel by magnetic separation, RCM must be crushed and screened to the desired gradation using conventional aggregate processing equipment.

Where the processed RCM contains some reclaimed asphalt pavement (RAP), which can occur when the RCM is derived from composite pavements, it is recommended that the RAP content in the RCM be limited to 20 percent maximum to prevent a reduction in bearing strength.(3)

Storage

Where RCM is available from different sources or concrete types, it should either be blended or maintained in separate stockpiles to ensure consistent material properties.

Washing

Washing of RCM aggregates is required by some agencies (Ohio, for example) to remove the dust as a measure to reduce potential tufa formation. To control tufa precipitate formation, only suitable RCM that does not contain appreciable unhydrated cement or free lime should be used for granular base applications.

Testing

Additional quality control testing (leachate testing) to assess the tufa precipitate potential of RCM aggregates may be necessary for granular base applications where subdrains are involved. A special procedure to identify the potential for tufa formation in steel slags was developed, which should be appropriate for RCM testing.(4)

ENGINEERING PROPERTIES

Some of the engineering properties of RCM that are of particular interest when RCM is used as a granular base material include gradation, absorption, specific gravity, stability, strength, durability, and drainage.

Gradation: RCM must be crushed and screened to satisfy AASHTO M147(5) and ASTM D2940(6) requirements for aggregates.

Absorption: High absorption is particularly noticeable in crushed fine material (minus 4.75 mm (No. 4 sieve)) derived from air-entrained concrete and ranges between 4 and 8 percent (compared with 2 percent or less for virgin concrete aggregates).(7)

Specific Gravity: The specific gravity of RCM aggregates (ranging from 2.0 for fines to 2.5 for coarse particles) is slightly lower than that of virgin aggregates.(7)

Stability: RCM has high friction angle, typically in excess of 40° and consequently demonstrates good stability and little postcompaction settlement.

Strength Characteristics: Processed RCM, being a 100 percent crushed material, is highly angular in shape. It exhibits California Bearing Ratio (CBR) values ranging from 90 to more than 140 (depending on the angularity of the virgin concrete aggregate and strength of the Portland cement matrix), which is comparable to crushed limestone aggregates.(8,9)

The inclusion of asphalt-coated particles in granular base material leads to reduced bearing capacity, varying with the proportion of asphalt-coated particles. Studies in Ontario, Canada, indicate that bearing strength is reduced below that expected for granular base (using natural aggregate) when the amount of blended asphalt coated particles exceeds 20 to 25 percent.(8)

Durability: RCM aggregates generally exhibit good durability with resistance to weathering and erosion. RCM is nonplastic, and is not susceptible to frost.

Drainage Characteristics: RCM (mainly coarse fraction) is free draining and is more permeable than conventional granular material because of lower fines content.

DESIGN CONSIDERATIONS

Processed RCM aggregates generally satisfy the requirements of AASHTO M147(5) and ASTM D2940.(6) Processed RCM is covered by conventional granular aggregate specifications in a number of jurisdictions.

Standard AASHTO pavement structural design procedures can be employed for granular base containing RCM aggregates. It is recommended that the appropriate structural number for RCM aggregates should be established by resilient modulus testing.

CONSTRUCTION PROCEDURES

Material Handling and Storage

The same methods and equipment used to store or stockpile conventional aggregates are applicable for RCM. However, additional care is required in stockpiling and handling RCM aggregates to avoid segregation of coarse and fine RCM.

Placing and Compacting

The same methods and equipment used to place and compact conventional aggregate can be used to place and compact RCM.

Quality Control

The same test procedures as used for conventional aggregate are appropriate for granular base applications when using RCM. Standard laboratory and field tests for compacted density and field measurement of compaction are given by AASHTO test methods T191(10), T205(11), T238(12) and T239.(13)

Special Considerations

Although there do not appear to be any environmental problems associated with leachate from RCM,(14,15) some jurisdictions require that stockpiles be separated (a minimum distance) from water courses because of the alkaline nature of RCM leachate.

Where RCM aggregates are used in granular base course applications in conjunction with subdrains, the following procedures are recommended to reduce the likelihood of leachate precipitates clogging the drainage system:(7)

- Wash the processed RCM aggregates to remove dust from the coarse particles.
- Ensure that any geotextile fabric surrounding the drainage trenches (containing the subdrains) does not intersect the drainage path from the base course (to avoid potential plugging with fines).

UNRESOLVED ISSUES

Further investigation of the propensity for tufa formation of RCM aggregates in granular base is needed. This should also include the development of standard methods to assess the suitability of RCM aggregates for base course applications where subdrains are used.

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INTRODUCTION

Although the use of reclaimed concrete material (RCM) in embankments or fill may not make the best use of the high quality aggregates associated with RCM, where no other applications are readily available, RCM can be satisfactorily used in this application. RCM aggregate is considered by many specifying agencies to be conventional aggregate. It requires minimal processing to satisfy the conventional soil and aggregate physical requirements for embankment or fill material.

The lower compacted unit weight of RCM aggregates compared with conventional mineral aggregates results in higher yield (greater volume for the same weight), and is therefore economically attractive to contractors. In addition, for large reconstruction projects, on-site processing and recycling of RCM is likely to result in economic benefits through reduced aggregate hauling costs.

PERFORMANCE RECORD

RCM has demonstrated satisfactory performance as an embankment or fill material. Its use is covered by special provisions to specifications in a number of jurisdictions. Desirable attributes of RCM for use in embankments or fill include high friction angle, good bearing strength, negligible plasticity, and good drainage characteristics.

Due to its high alkalinity, RCM in contact with aluminum or galvanized steel pipes can cause corrosion in the presence of moisture.

A potential for tufa-like precipitates to leach from RCM in granular base applications has been described in the literature,(1) and may also be a consideration in embankment or fill applications.

MATERIAL PROCESSING REQUIREMENTS

Crushing and Screening

Prior to its use, any reinforcing steel must be removed and RCM must be broken or crushed and screened to satisfy the maximum size and gradation requirements for use in embankment construction.

Where the processed RCM contains some reclaimed asphalt pavement (RAP), which can occur when the RCM is derived from composite pavements, it is recommended that the RAP content in the RCM be limited to 20 percent to prevent a reduction in bearing strength due to the presence of RAP.(2)

Washing

Washing of RCM aggregates is required by some agencies to remove the dust as a measure to reduce tufa formation potential. To control tufa precipitate formation, only suitable RCM that does not contain significant quantities of unhydrated cement or free lime should be used for embankment or fill applications.

Testing

Additional quality control testing (leachate testing) may be necessary to assess the tufa precipitate potential of RCM aggregates for embankment applications. A special procedure to identify the potential for tufa formation in steel slags was developed, which should be appropriate for RCM testing.(3)

ENGINEERING PROPERTIES

Some of the engineering properties of RCM that are of particular interest when RCM is used as an embankment or fill material include gradation, specific gravity, stability, strength, durability, drainage, and corrosivity.

Gradation: RCM must be crushed and screened to satisfy AASHTO M145(4), and ASTM D2940(5) gradation requirements for embankment or fill aggregates.

Specific Gravity: The specific gravity of RCM aggregates (ranging from 2.0 for fines to 2.5 for coarse particles) is slightly lower than that of virgin aggregates.(6)

Stability: RCM has high friction angle, typically in excess of 40° and consequently demonstrates good stability and little postcompaction settlement.

Strength Characteristics: Processed RCM, being 100 percent crushed material, is highly angular in shape. It exhibits California Bearing Ratio (CBR) values ranging from 90 to more than 140 percent (depending on the angularity of the virgin concrete aggregate and strength of the Portland cement matrix), which is comparable to crushed limestone aggregates.(7,8)

Durability: RCM aggregates generally exhibit good durability with resistance to weathering and erosion.

Drainage Characteristics: RCM (mainly coarse fraction) is free draining (more permeable than conventional granular material due to lower fines content). RCM is nonplastic and is not susceptible to frost.

Corrosivity: The high alkalinity of RCM (pH greater than 11) can result in corrosion to aluminum or galvanized steel pipes in direct contact with RCM and in the presence of moisture.(9)

DESIGN CONSIDERATIONS

The design requirements for RCM in embankment construction are the same as for conventional aggregates. There are no standard specifications covering RCM use as embankment or fill material.

Structural design procedures for embankments or fill containing RCM are the same as design procedures for embankments or fill containing conventional materials.

CONSTRUCTION PROCEDURES

Material Handling and Storage

The same methods and equipment used to store or stockpile conventional aggregates are applicable for reclaimed concrete material. Some jurisdictions (Ontario, Canada, for example) may restrict stockpiling and placement of RCM near watercourses to minimize the impact of the alkaline leachate on ambient water quality. Appropriate procedures may also be required to avoid segregation of coarse and fine materials during handling and storage. These include stockpile construction using radial stackers, with remixing using a front-end loader or bulldozer prior to load-out, and care during load-out and placement.

Placing and Compacting

Due to their high angularity, additional effort (for instance using vibratory rollers) may be required to compact RCM to its maximum density. The processor may be required to satisfy moisture content criteria according to AASHTO T99,(10) in order to achieve good compactibility. This usually requires the addition of water during placement and compaction.

Quality Control

The same test procedures used for conventional aggregate are appropriate for embankment applications when using RCM. Standard laboratory and field tests for compacted density and field measurement of compaction are given by AASHTO test methods: T191(11), T205(12), T238(13) and T239.(14)

Special Considerations

To avoid corrosion problems, RCM should not be placed in contact with aluminum or galvanized steel pipes. Caution is also warranted in locations subject to wet conditions, as tufa-like precipitates ($CaCO_3$) associated with the leachate from RCM may develop upon exposure to the atmosphere.(1)

UNRESOLVED ISSUES

Although problems associated with tufa precipitate formation in embankments containing RCM have not been identified, a study of the subject would provide useful technical data to better define the nature and degree of the problem, and to affirm the use of RCM in embankment construction.

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ORIGIN

There are two types of roofing shingle scraps. They are referred to as tear-off roofing shingles, and roofing shingle tabs, also called prompt roofing shingle scrap. Tear-off roofing shingles are generated during the demolition or replacement of existing roofs. Roofing shingle tabs are generated when new asphalt shingles are trimmed during production to the required physical dimensions. The quality of tear-off roofing shingles can be quite variable.

Approximately 10 million metric tons (11 million tons) of asphalt roofing shingle scrap are generated each year in the United States.(1) It is estimated that 90 to 95 percent of this material is from residential roof replacement ("tear-offs"), with the remainder being leftover material from shingle production ("roofing shingle tabs").

Roofing shingles are produced by impregnating either organic felt produced from cellulose fibers, or glass felt produced from glass fibers, with a hot saturant asphalt, which is subsequently coated on both sides with more asphalt and finally surfaced with mineral granules. Most roofing shingles produced are of the organic felt type. The saturant and coating asphalt need not be the same. Both saturant and coating asphalts are produced by "blowing," a process in which air is bubbled through molten asphalt flux. The heat and oxygen act to change the characteristics of the asphalt. The process is monitored, and the "blowing" is stopped when the desired characteristics have been produced.

The largest component of roofing shingles (60 to 70 percent by mass) is the mineral material. There are several different types in each shingle.(2) They can include ceramic granules (comprising crushed rock particles, typically trap rock, coated with colored, ceramic oxides), lap granules (coal slag ground to roughly the same size as the ceramic granules), backsurfacer sand (washed, natural sand used in small quantities to keep packaged shingles from sticking together), and asphalt stabilizer (powdered limestone that is mixed into the asphalt).

Specifications for roofing shingles are set out in ASTM D255(3) and ASTM D3462.(4)

CURRENT MANAGEMENT OPTIONS

Recycling

Small quantities of prompt shingle scrap, typically shredded to 38 mm (1.5 in) and smaller, have been used as a gravel substitute for the wearing surface for rural roads and farm lanes. Increasing use of processed tabs or prompt roofing shingle scrap and, to a much lesser extent, tear-off roofing material is being made as a modifier to hot mix asphalt pavements, stone mastic asphalt pavements, and cold mix asphalt patching material.

Disposal

Most roofing shingle scrap is presently disposed of by landfilling.

MARKET SOURCES

Roofing shingle tabs (prompt shingle scrap) can be obtained directly from shingle manufacturers. Tear-off shingle scrap can be obtained directly from roofing contractors or disposal sites that accept the scrap. Information on tab or prompt scrap sources can be obtained from the roofing shingle suppliers or manufacturers.

The general composition of prompt roofing shingle scrap is identical to the shingles from which it is cut except for substantially smaller dimensions. Proportions of the primary components of asphalt shingles are listed in Table 15-1.

Table 15-1. Components of asphalt shingles.(2)

Component	Approximate Amount % by Weight	Notes
Asphalt Cement	25-35	Generally of two types (saturant and coating)
Granular Material	60-70	Ceramic granules, headlap granules, backsurfacer sand, and asphalt stabilizer
Backing	5-15	Cellulose or glass felt

Tear-off roofing shingle scrap typically contains small percentages of foreign materials, including nails, felt underlayment, metal flashings, and wood, as well as waterproofing and insulation materials. The asphalt cement binder component of tear-off roofing shingles is generally old, severely weathered and oxidized.

The specification for glass felt shingles (ASTM D3462) permits asbestos fibers. Although not widely used, processing of shingles containing asbestos fibers can present a health risk to workers handling the material.

HIGHWAY USES AND PROCESSING REQUIREMENTS

Asphalt Cement Modifier

Recent tests strongly suggest that roofing shingle tabs (prompt roofing shingle scrap) can be used as an asphalt cement modifier. The incorporation of roofing shingles into asphalt mixes results in reduced asphalt cement requirements and tends to result in stiffer mixes, with improved temperature susceptibility and rut resistance.

Prompt roofing shingle scrap is mainly produced in tabs approximately 285 mm long by 9.5 mm wide by 3 mm thickness (11.5 in by 3/8 in by 1/8 in) which must then be processed to suitable size for introduction into the hot mix asphalt. The asphalt tabs are processed in two stages. The tabs are first shredded using a rotary shredder consisting of two slow-speed blades turning at approximately 50 revolutions per minute. This reduces the chips into smaller but still quite coarse pieces. The smaller pieces are then reduced to a nominal size of about 9.5 mm (3/8 in) or finer using a high-speed hammermill operating at about 800 to 900 revolutions per minute. To keep the roofing shingle material from agglomerating during processing, it is usually passed through the shredding equipment only once, or the material is kept cool by watering at the hammer mill, then stockpiled. The application of water is not very desirable since the processed material becomes quite wet and must be dried prior to introduction into hot mix asphalt.

Tear-off roofing shingle could potentially be used as an asphalt modifier, but tear-off shingle scrap is much more difficult to process because of the presence of contaminants and debris such as nails, wood, insulation, etc. Any debris must be removed to prevent equipment damage during size reduction.

Aggregate Substitute and Mineral Filler

Roofing shingles incorporated into asphalt paving mixes not only modify the binder, but also, depending on the size of the shredded material, function like an aggregate or mineral filler. Organic felt and glass felt particles in particular tend to function like a mineral filler substitute.

MATERIAL PROPERTIES

Roofing shingles are unlike other by-product or secondary materials in that they contain components of fine aggregate, mineral filler, and asphalt cement. There are also differences between the types of shingles (organic and glass felt) produced. As shown in Table 15-2, organic felt shingles can be expected to exhibit higher moisture content and lower specific gravity than glass felt shingles. Shredded organic felt shingle scrap also exhibits much higher absorption than shredded fiberglass shingle scrap.

Table 15-2. Typical physical properties of shredded roofing shingle scrap.[5]

Property	Value
Maximum Moisture Content	
Organic Felt Shingles	< 10%
Glass Felt Shingles	< 3%
Specific Gravity	
Organic Felt Shingles	1.29
Glass Felt Shingles	1.37

Typical physical properties of recovered asphalt cement and the gradation of mineral granules in shingle scrap are listed in Table 15-3. Asphalt cement in old roofing shingles undergoes oxidative age hardening and stearic hardening (a hardening process in which solid compounds separate from volatile oils in the asphalt cement). Consequently, the asphalt cement in old tear-off roofing shingles is somewhat harder than new asphalt. Although the stearic hardening process has been demonstrated to be reversible by reheating and/or solubilizing,[1] oxidative age hardening is not reversible.

Table 15-3. Typical physical properties of recovered asphalt cement and gradation of recovered mineral material from roofing shingle scrap.[5]

Properties	New Organic Felt	New Fiberglass Felt	Old Roofing Shingles
Binder Content, %	Approx. 28%	Approx. 28%	30-40%
Binder Properties:			
Softening Point, °C (°F)	52-102 (125-215)	52-102 (125-215)	66-82 (150-180)
Penetration, dmm (25°C)	23-70	23-70	20 minimum
Ductility, cm (5 cm/min, 25°C)	NA	NA	25 minimum
Flash Point, °C (°F) COC	>260 (500)	>260 (500)	232 (450) minimum
Mineral Material Cumulative Percent Passing			
4.75 mm (No.4)	100	100	95-100
2.36 mm (No.8)	69	89	55-75
1.0 mm (No.20)	45	65	15-35
0.3 mm (No.50)	5	11	0-15
0.15 mm (No.100)	0	1	0-10

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INTRODUCTION

Roofing shingle tabs and, to a much lesser extent, tear-off roofing material waste can be used as a replacement for a portion of the asphalt cement and aggregate in hot mix asphalt and as an ingredient in cold mix asphalt patching material. When used in asphalt paving applications, the properties of constituent materials must be well defined and consistent. Since the composition and properties of old, tear-off roofing shingles are likely to include foreign materials (such as nails, metal flashing, and felt underlayment) as well as asbestos fibers, and can vary widely, prompt scrap that has been left over from the manufacture of new roofing shingles, and which exhibits more consistent properties, is preferred for incorporation into asphalt mixtures.

PERFORMANCE RECORD

Laboratory studies undertaken during the 1980's suggest that asphalt mixtures containing roofing shingle scrap could exhibit mix design properties similar to that of conventional asphalt mixtures.(1) Utilization of roofing shingle scrap in hot mix asphalt pavements began in 1990 with trial sections placed in Minnesota.(2) Since then, interest in the use of asphalt paving mixtures containing roofing shingle scrap has increased, with additional studies and trials in Minnesota, Indiana, Illinois, Missouri, New Jersey, and Ontario, Canada.

Typical addition rates for roofing shingle scrap in hot mix asphalt have ranged from 3 to 6 percent (by mass). Evaluations of a New Jersey trial pavement section after a few years of service have indicated that performance similar to conventional hot mix asphalt pavements can be expected, with no significant differences in rut depth, cracking, or skid resistance.(3)

Roofing shingle scrap has also been used in hot mix asphalt for private sector (commercial/ industrial) work in Florida, Minnesota, and Michigan. It has been cited as contributing to improved performance of cold mix asphalt repair materials (pothole repair materials) in Illinois and New Jersey.(4,5) Laboratory studies indicate that prompt roofing shingle scrap can also be used in stone-mastic asphalt applications, with the fiber contained in the shingle material effectively acting as an anti-draindown additive, preventing the asphalt cement from running off this relatively rich, coarse-textured asphalt mixture.(6)

Hazardous waste regulatory leachate test data (TCLP) indicate that the leachate from processed asphalt roofing shingle scrap is well below allowable EPA limits.(7) However, tear-off roofing shingles can contain significant concentrations of polynuclear aromatic hydrocarbons that are present in roofing tar, and there is some concern that asphalt plant air emissions could be impacted during hot mix asphalt production.

When properly designed and executed, the use of processed roofing shingle scrap in hot mix asphalt can result in similar or enhanced properties to standard asphalt concrete pavements, with reductions in requirements for virgin asphalt cement (by approximately 0.5 to 1.5 percent). However, processing costs involved must be assessed against the reduction in virgin asphalt cement and aggregates to properly evaluate the viability of using roofing shingles in pavements.

MATERIAL PROCESSING REQUIREMENTS

Quality Control

No special quality control techniques are required for prompt roofing shingle scrap; however, tear-off shingle scrap is much more difficult to process due to the presence of contaminants and debris such as nails, wood, insulation, etc. Any debris must be removed to prevent equipment damage during size reduction. There is no standard processing equipment to accomplish this task.

Shredding

Roofing shingle scrap used in asphalt paving mixes is typically shredded into pieces approximately 13 mm (1/2 in) in size and smaller using a shingle shredding machine that consists of a rotary shredder and/or a high-speed hammermill.

Screening

Shredded shingles are typically discharged from the shredder or hammermill and screened to the desired gradation and stockpiled. Experience indicates that the size of the processed pieces should be no larger than approximately 13 mm (1/2 in) to ensure complete digestion of the roofing shingle scrap and uniform incorporation into the hot mix asphalt.(8) Scrap shingle greater than 13 mm (1/2 in) in size does not readily disperse, functioning much like aggregate. Particles sized too small can release the fibers, which act as a filler substitute.(9)

Blending

Processed roofing shingle material can resolidify during stockpiling, necessitating reprocessing and rescreening prior to introduction to the hot mix plant. To mitigate this problem, processed roofing shingle scrap may be blended with a carrier material such as sand or recycled asphalt to prevent the particles from sticking together.

Watering

To keep the roofing shingle material from agglomerating during processing, it is usually passed through the shredding equipment only once, or the material is kept cool by watering at the hammermill. However, the application of water is not very desirable since the processed material becomes quite wet and must be dried prior to introduction into hot mix asphalt.

ENGINEERING PROPERTIES

Some of the properties of roofing shingle tabs that are of particular interest when roofing shingles are used in asphalt paving include asphalt content, asphalt hardness (penetration/viscosity), and aggregate gradation.

Asphalt Cement (AC) Content: The asphalt cement contained in prompt roofing shingle scrap is typically 25 to 35 percent by weight. Accurate determination of the prompt shingle scrap asphalt content and penetration is not possible using conventional Abson recovery techniques.(1) Extended soaking periods are required to extract and determine the available asphalt.

Asphalt Hardness (Viscosity/ Penetration): The precise determination of the AC viscosity and penetration is not possible because the roofing shingle asphalt is much harder than that normally used in asphalt concrete paving mixtures and contains fibers (which tend to stiffen asphalt concrete mixtures). Roofing shingle scrap must be blended with a much softer (higher penetration/lower viscosity) asphalt cement binder for use in hot mix asphalt.

Gradation: Roofing shingle aggregates (granules) consist of minus 4.75 mm (No.4 sieve size) particles, which supplement the fine aggregate fraction of hot mix asphalt.

Some of the mix properties that are of interest when roofing shingles are incorporated into asphalt pavements include the stiffening influence of roofing shingle fibers, strength, and stripping.

Stiffening Influence of Roof Shingle Scrap: Due largely to the influence of shingle fibers, laboratory studies indicate that incorporating prompt roofing shingle scrap in asphalt mixes tends to improve the high temperature susceptibility and rut-resistant properties of the mix.(6,9,10) Test results also indicate improved fatigue life of pavements with increasing roofing shingle scrap content.(10)

Strength Characteristics: The use of prompt roofing shingle scrap (ranging from 3 to 5 percent by mass of the total mix) results in a denser pavement under compactive effort.(6) While cold tensile strengths are reduced by the addition of roofing shingle scrap,(6) resilient modulus testing indicates that potential for low-temperature cracking is not substantially affected.(3,6,10)

The strain capacity of mixes with scrap shingles appears to be related to shingle type. Mixes containing organic felt shingle scrap exhibit slightly higher strain capacity than those with glass felt shingle scrap.(6)

Stripping: The moisture sensitivity of asphalt mixtures (an indication of stripping potential) does not appear to be significantly affected by the addition of prompt roofing shingle scrap,(6,9) but could be adversely affected by old, used roofing shingle scrap.(6)

DESIGN CONSIDERATIONS

Mix Design

Asphalt mixes containing roofing shingle scrap can be designed using standard laboratory procedures. The specifications for new roofing shingles are set out in ASTM D255(11) and ASTM D3462,(12) which provide information on the material constituents.

Roofing shingle scrap (both organic felt and/or fiberglass felt) incorporated into asphalt paving mixes modifies the binder and also acts as a fine aggregate and mineral filler. Typically, an increase in filler content lowers the optimum asphalt cement content and increases the density and stability of the mix. Higher filler content can adversely affect durability due to reduction of voids in the mineral aggregate and optimum asphalt cement content. Also, excessive mineral filler can increase the surface area of the aggregate, reducing the asphalt film thickness.

Roofing shingle scrap may be susceptible to moisture-related damage (stripping) and, therefore, the mix design should include a stripping resistance or retained stability test such as AASHTO T283(13) or MTO LS-283.(14)

Structural Design

Conventional AASHTO pavement design methods are appropriate for asphalt pavements incorporating roof shingle scrap in the mix.

CONSTRUCTION CONSIDERATIONS

Material Handling and Storage

Accommodation must be made to avoid agglomeration of processed roofing shingle scrap, which can result in poor dispersion in the paving mix. One method of controlling agglomeration is to shred the material at the asphalt plant, immediately prior to introduction into the mixer. However, this generally requires that a shredder be installed at each plant and may not be practical.

Mixing, Placing and Compacting

Processed roofing shingle scrap can be blended with fine aggregates in a pugmill (at a ratio of three parts roofing shingle scrap to one part fine aggregate).(8) The fine aggregate acts as a carrier for the shingle scrap, preventing agglomeration and producing a material that can be stockpiled, handled, and fed through the existing recycle system of a batch or drum mix plant.

The same methods and equipment used for conventional pavements are applicable to asphalt pavements containing roofing shingle scrap.

Quality Control

The same field testing procedures used for conventional hot mix asphalt mixes should be used for mixes containing roofing shingle scrap. Mixes should be sampled in accordance with AASHTO T168(15), and tested for specific gravity in accordance with ASTM D2726(16) and in-place density in accordance with ASTM D2950.(17)

UNRESOLVED ISSUES

There is a need to establish standard mix design methods for use in designing asphalt pavements using roofing shingle scrap. There is also a need to verify the long-term performance of hot mix asphalt incorporating suitably processed roofing shingle material with respect to fatigue, rutting, and low-temperature cracking. The recyclability of asphalt pavements incorporating roofing shingle material at the end of the service life of the pavement needs to be evaluated along with life cycle cost analysis to determine the economic viability of using roofing shingle scrap.

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ORIGIN

Approximately 280 million tires are discarded each year by American motorists, approximately one tire for every person in the United States. Around 30 million of these tires are retreaded or reused, leaving roughly 250 million scrap tires to be managed annually. About 85 percent of these scrap tires are automobile tires, the remainder being truck tires. Besides the need to manage these scrap tires, it has been estimated that there may be as many as 2 to 3 billion tires that have accumulated over the years and are contained in numerous stockpiles.(1)

Scrap tires can be managed as a whole tire, a slit tire, a shredded or chipped tire, as ground rubber, or as a crumb rubber product.

Whole Tires

A typical scrapped automobile tire weighs 9.1 kg (20 lb). Roughly 5.4 kg (12 lb) to 5.9 kg (13 lb) consists of recoverable rubber, composed of 35 percent natural rubber and 65 percent synthetic rubber. Steel-belted radial tires are the predominant type of tire currently produced in the United States.(2) A typical truck tire weighs 18.2 kg (40 lb) and also contains from 60 to 70 percent recoverable rubber. Truck tires typically contain 65 percent natural rubber and 35 percent synthetic rubber.(2) Although a majority of truck tires are steel-belted radials, there are still a number of bias ply truck tires, which contain either nylon or polyester belt material.

Slit Tires

Slit tires are produced in tire cutting machines. These cutting machines can slit the tire into two halves or can separate the sidewalls from the tread of the tire.

Shredded or Chipped Tires

In most cases the production of tire shreds or tire chips involves primary and secondary shredding. A tire shredder is a machine with a series of oscillating or reciprocating cutting edges, moving back and forth in opposite directions to create a shearing motion, that effectively cuts or shreds tires as they are fed into the machine. The size of the tire shreds produced in the primary shredding process can vary from as large as 300 to 460 mm (12 to 18 in) long by 100 to 230 mm (4 to 9 in) as wide, down to as small as 100 to 150 mm (4 to 6 in) in length, depending on the manufacturer, model, and condition of the cutting edges. The shredding process results in exposure of steel belt fragments along the edges of the tire shreds.(3) Production of tire chips, which are normally sized from 76 mm (3 in) down to 13 mm (1/2 in), requires two-stage processing of the tire shreds (i.e., primary and secondary shredding) to achieve adequate size reduction. Secondary shredding results in the production of chips that are more equidimensional than the larger size shreds that are generated by the primary shredder, but exposed steel fragments will still occur along the edges of the chips.(3)

Ground Rubber

Ground rubber may be sized from particles as large as 19 mm (3/4 in) to as fine as 0.15 mm (No. 100 sieve) depending on the type of size reduction equipment and the intended application.

The production of ground rubber is achieved by granulators, hammermills, or fine grinding machines. Granulators typically produce particles that are regularly shaped and cubical with a comparatively low-surface area. The steel belt fragments are removed by a magnetic separator. Fiberglass belts or fibers are separated from the finer rubber particles, usually by an air separator. Ground rubber particles are subjected to a dual cycle of magnetic separation, then screened and recovered in various size fractions.(4)

Crumb Rubber

Crumb rubber usually consists of particles ranging in size from 4.75 mm (No. 4 sieve) to less than 0.075 mm (No. 200 sieve). Most processes that incorporate crumb rubber as an asphalt modifier use particles ranging in size from 0.6 mm to 0.15 mm (No. 30 to No. 100 sieve).

Three methods are currently used to convert scrap tires to crumb rubber. The crackermill process is the most commonly used method. The crackermill process tears apart or reduces the size of tire rubber by passing the material between rotating corrugated steel drums. This process creates an irregularly shaped torn particle with a large surface area. These particles range in size from approximately 5 mm to 0.5 mm (No. 4 to No. 40 sieve) and are commonly referred to as ground crumb rubber. The second method is the granulator process, which shears apart the rubber with revolving steel plates that pass at close tolerance, producing granulated crumb rubber particles, ranging in size from 9.5 mm (3/8 in) to 0.5 mm (No. 40 sieve). The third process is the micro-mill process, which produces a very fine ground crumb rubber in the size range from 0.5 mm (No. 40 sieve) to as small as 0.075 mm (No. 200 sieve).(4)

In some cases, cryogenic techniques are also used for size reduction. Essentially, this involves using liquid nitrogen to reduce the temperature of the rubber particles to minus 87°C (-125°F), making the particles quite brittle and easy to shatter into small particles. This technique is sometimes used before final grinding.(5)

Additional information on the production and use of scrap tire products can be obtained from:

Scrap Tire Management Council
1400 K Street, N.W.
Washington, D.C. 20005

CURRENT MANAGEMENT OPTIONS

Recycling

About 7 percent of the 250 million scrap tires generated annually are exported to foreign countries, 8 percent are recycled into new products, and roughly 40 percent are used as tire-derived fuel, either in whole or chipped form.(1)

Currently, the largest single use for scrap tires is as a fuel in power plants, cement plants, pulp and paper mill boilers, utility boilers, and other industrial boilers. At least 100 million scrap tires were used in 1994 as an alternative fuel either in whole or chipped form.(1)

At least 9 million scrap tires are processed into ground rubber annually. Ground tire rubber is used in rubber products (such as floor mats, carpet padding, and vehicle mud guards), plastic products, and as a fine aggregate addition (dry process) in asphalt friction courses. Crumb rubber has been used as an asphalt binder modifier (wet process) in hot mix asphalt pavements.(1)

As previously noted, of the roughly 30 million tires that are not discarded each year, most go to retreaders, who retread about one-third of the tires received. Automobile and truck tires that are retreaded are sold and returned to the marketplace. Currently there are roughly 1,500 retreaders operating in the United States, but the number is shrinking because there is a decline in the market for passenger car retreads. The truck tire retread business is increasing and truck tires can be retreaded three to seven times before they have to be discarded.(1)

Disposal

Approximately 45 percent of the 250 million tires generated annually are disposed of in landfills, stockpiles, or illegal dumps.

As of 1994, at least 48 states have some type of legislation related to landfilling of tires, including 9 states that ban all tires from landfills. There are 16 states in which whole tires are banned from landfills. Thirteen other states require that tires be cut in order to be accepted at landfills.(6)

MARKET SOURCES

About 80 percent of all scrap tires are handled by retail tire vendors. The remaining 20 percent are handled by auto dismantlers. These two industrial groups, while not the generators of scrap tires, collect and store tires until they are picked up by transporters, sometimes referred to as "tire jockeys." These transporters take the tires to retreaders, reclaimers, and grinders or slitters or to tire disposal sites (landfills, tire stockpiles, or illegal dumps).(1)

Figure 16-1 presents a graphical overview of the scrap tire industry.

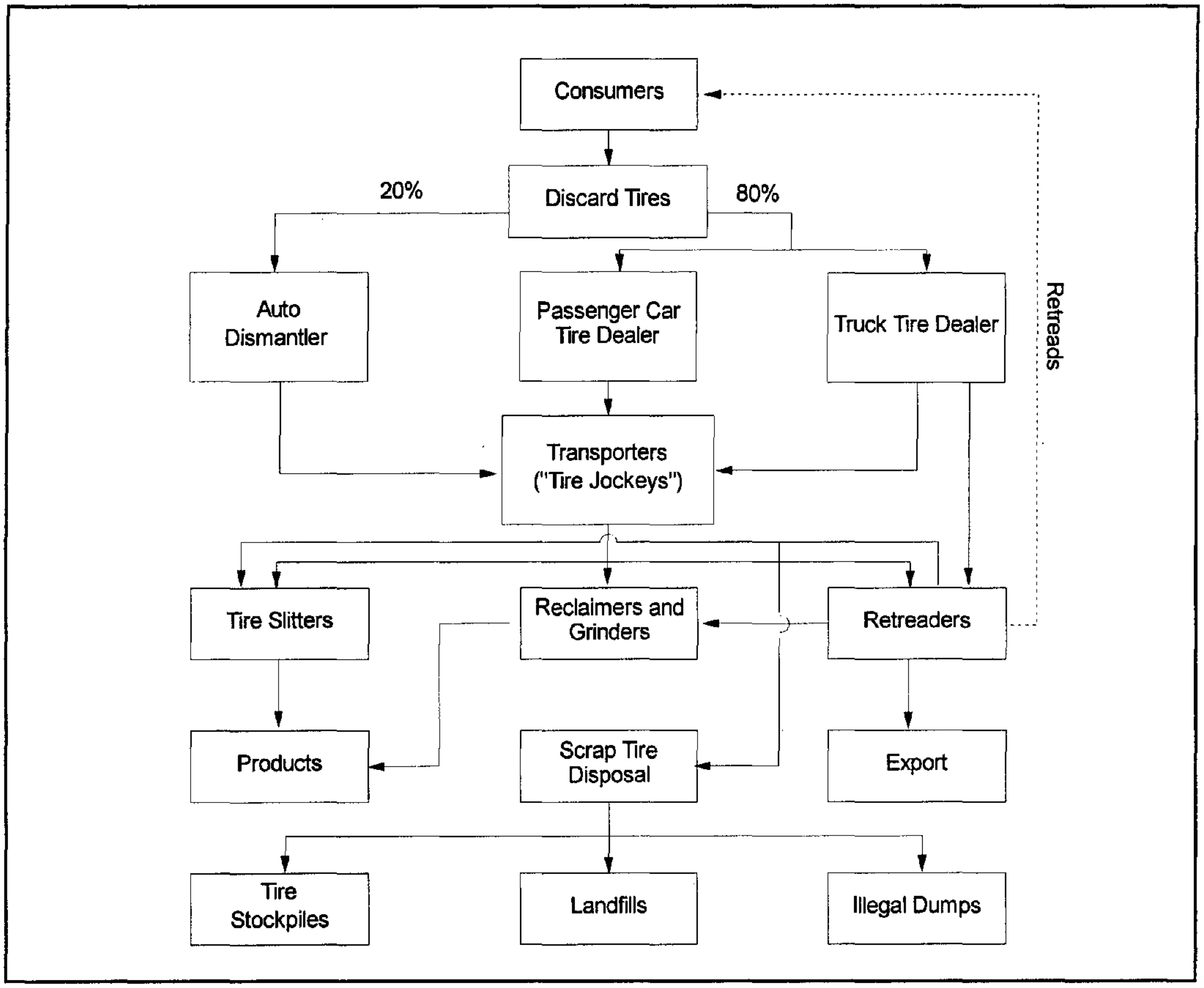

Figure 16-1. Overview of the scrap tire industry.

Since tires are combustible, tire storage sites can be potential fire hazards. Care must be taken to safeguard against carelessness or accidental ignition, which can occur at tire storage facilities.(7)

Tire shreds or chips would normally be available from tire shredder operators. Ground rubber or crumb rubber would normally be available from scrap tire processors There are probably 100 or more tire shredders in the United States, but there are only about 15 to 20 scrap tire processors.

HIGHWAY USES AND PROCESSING REQUIREMENTS

Embankment Construction - Shredded or Chipped Tires

Shredded or chipped tires have been used as a lightweight fill material for construction of embankments. However, recent combustion problems at three locations have prompted a reevaluation of design techniques when shredded or chipped tires are used in embankment construction.(7)

Aggregate Substitute - Ground Rubber

Ground rubber has been used as a fine aggregate substitute in asphalt pavements. In this process, ground rubber particles are added into the hot mix as a fine aggregate in a gap-graded friction course type of mixture. This process, commonly referred to as the dry process, typically uses ground rubber particles ranging from approximately 6.4 mm (1/4 in) down to 0.85 mm (No. 20 sieve).(4) Asphalt mixes in which ground rubber particles are added as a portion of the fine aggregate are referred to as rubberized asphalt.

Asphalt Modifier - Crumb Rubber

Crumb rubber can be used to modify the asphalt binder (e.g., increase its viscosity) in a process in which the rubber is blended with asphalt binder (usually in the range of 18 to 25 percent rubber). This process, commonly referred to as the wet process, blends and partially reacts crumb rubber with asphalt cement at high temperatures to produce a rubberized asphalt binder. Most of the wet processes require crumb rubber particles between 0.6 mm (No. 30 sieve) and 0.15 mm (No. 100 sieve) in size. The modified binder is commonly referred to as asphalt-rubber.

Asphalt-rubber binders are used primarily in hot mix asphalt paving, but are also used in seal coat applications as a stress absorbing membrane (SAM), a stress absorbing membrane interlayer (SAMI), or as a membrane sealant without any aggregate.

Retaining Walls - Whole and Slit Tires

Although not a direct highway application, whole tires have been used to construct retaining walls. They have also been used to stabilize roadside shoulder areas and provide channel slope protection. For each application, whole tires are stacked vertically on top of each other. Adjacent tires are then clipped together horizontally and metal posts are driven vertically through the tire openings and anchored into the underlying earth as necessary to provide lateral support and prevent later displacement. Each layer of tires is filled with compacted earth backfill.(8) This type of retaining wall construction was initially performed in California.

Slit scrap tires can be used as reinforcement in embankments and tied-back anchor retaining walls. By placing tire sidewalls in interconnected strips or mats and taking advantage of the extremely high tensile strength of the sidewalls, embankments can be stabilized in accordance with the reinforced earth principles. Sidewalls are held together by means of metal clips when reinforcing embankments, or by a cross-arm anchor bar assembly when used to anchor retaining walls.(8)

MATERIAL PROPERTIES

Physical Properties

Shredded Tires

Tire shreds are basically flat, irregularly shaped tire chunks with jagged edges that may or may not contain protruding, sharp pieces of metal, which are parts of steel belts or beads. As previously noted, the size of tire shreds may range from as large as 460 mm (18 in) to as small as 25 mm (1 in), with most particles within the 100 mm (4 in) to 200 mm (8 in) range. The average loose density of tire shreds varies according to the size of the shreds, but can be expected to be between 390 kg/m^3 (24 lb/ft^3) to 535 kg/m^3 (33 lb/ft^3). The average compacted density ranges from 650 kg/m^3 (40 lb/ft^3) to 840 kg/m^3 (52 lb/ft^3).(3)

Tire Chips

Tire chips are more finely and uniformly sized than tire shreds, ranging from 76 mm (3 in) down to approximately 13 mm (1/2 in) in size. Although the size of tire chips, like tire shreds, varies with the make and condition of the processing equipment, nearly all tire chip particles can be gravel sized. The loose density of tire chips can be expected to range from 320 kg/m^3 (20 lb/ft^3) to 490 kg/m^3 (30 lb/ft^3). The compacted density of tire chips probably ranges from 570 kg/m^3 (35 lb/ft^3) to 730 kg/m^3 (45 lb/ft^3).(9) Tire chips have absorption values that range from 2.0 to 3.8 percent.(10)

Ground Rubber

Ground rubber particles are intermediate in size between tire chips and crumb rubber. The particle sizing of ground rubber ranges from 9.5 mm (3/8 in) to 0.85 mm (No. 20 sieve).

Crumb Rubber

Crumb rubber used in hot mix asphalt normally has 100 percent of the particles finer than 4.75 mm (No. 4 sieve). Although the majority of the particles used in the wet process are sized within the 1.2 mm (No. 16 sieve) to 0.42 mm (No. 40 sieve) range, some crumb rubber particles may be as fine as 0.075 mm (No. 200 sieve). The specific gravity of crumb rubber is approximately 1.15, and the product must be free of fabric, wire, or other contaminants.(4)

Chemical Properties

Tire chips and tire shreds are nonreactive under normal environmental conditions. The principal chemical component of tires is a blend of natural and synthetic rubber, but additional components include carbon black, sulfur, polymers, oil, paraffins, pigments, fabrics, and bead or belt materials.(2)

Mechanical Properties

Limited data are available on the shear strength of tire chips, while little or no such data are available on the shear strength of tire shreds. The wide variation in shred size makes it difficult, if not virtually impossible, to find a large enough apparatus to perform a meaningful shear test. Although the shear strength characteristics of tire chips vary according to the size and shape of the chips, internal friction angles were found to range from 19° to 26°, while cohesion values ranged from 4.3 kPa (90 lb/ft^2)to 11.5 kPa (90 to 240 lb/ft^2). Tire chips have a permeability coefficient ranging from 1.5 to 15 cm/sec.(10)

Other Properties

Scrap tires have a heating value ranging from 28,000 kJ/kg (12,000 Btu/lb) to 35,000 kJ/kg (15,000 Btu/lb).(2) As a result, given appropriate conditions, scrap tire combustion is possible and must be considered in any application.

Tire chips can also be expected to exhibit high insulating properties. If tire chips are used as a fill material in subgrade applications, reduced depth of frost penetration compared with that of granular soil can be expected.(11)

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INTRODUCTION

Scrap tire rubber can be incorporated into asphalt paving mixes using two different methods referred to as the wet process and the dry process. In the wet process, crumb rubber acts as an asphalt cement modifier, while in the dry process, granulated or ground rubber and/or crumb rubber is used as a portion of the fine aggregate. In both cases, crumb rubber is sometimes referred to as crumb rubber modifier (CRM) because its use modifies the properties of the resultant hot mix asphalt concrete product.

The wet process can be used for hot mix asphalt paving mixtures, as well as chip seals or surface treatments. The wet process can also be used to prepare rubberized joint and crack sealants, which are not included in the scope of this document. In the wet process, crumb rubber is blended with asphalt cement (usually in the range of 18 to 25 percent rubber) before the binder is added to the aggregate.

When asphalt cement and CRM are blended together, the CRM reacting with the asphalt cement swells and softens. This reaction is influenced by the temperature at which the blending occurs, the length of time the temperature remains elevated, the type and amount of mechanical mixing, the size and texture of the CRM, and the aromatic component of the asphalt cement.

The reaction itself involves the absorption of aromatic oils from the asphalt cement into the polymer chains that comprise the major structural components of natural and synthetic rubber in CRM. The rate of reaction between CRM and asphalt cement can be increased by enlarging the surface area of the CRM and increasing the temperature of the reaction. The viscosity of the asphalt-CRM blend is the primary parameter that is used to monitor the reaction.(1) The specified reaction time should be the minimum time, at a prescribed temperature, that is required to stabilize the binder viscosity.

When CRM is blended with asphalt cement in the wet process, the modified binder is referred to as asphalt-rubber. To date, most of the experience with the use of CRM in asphalt paving has been with the wet process.

Asphalt-rubber binders are used in chip-seal coats as well as hot mix asphalt paving. Chip-seal coat applications using asphalt-rubber binders have become known as stress-absorbing membranes (SAM). When an asphalt-rubber chip seal or SAM is overlaid with hot mix asphalt, the chip seal is referred to as a stress-absorbing membrane interlayer (SAMI).

Early applications were batch wet processes and were based on the McDonald technology, which was developed in the early 1960's by Charles McDonald, a City of Phoenix engineer, and in the

1970's by Arizona Refining Company (ARCO). There are numerous patents related to the McDonald technology, some of which have expired and some of which have not.(1,2)

A continuous blending technology was developed in Florida in the late 1980's and is frequently referred to as the Florida wet process. In this process, a fine 0.18 mm (No. 80 sieve) CRM is blended with asphalt cement in a continuous process. The Florida technology differs from the McDonald process in several respects: lower percentages of CRM (from 8 to 10 percent rubber), smaller CRM particle size, lower mixing temperature, and shorter reaction time. The Florida wet process has not as yet been patented.(1)

Terminal blending is a wet process with the capability of blending or combining asphalt cement and CRM and holding the product for extended periods of time. This asphalt-rubber product has a shelf life and is blended at an asphalt cement terminal using either batch or continuous blending. Individual state highway agencies are now developing their own products with this technology, since it is not patented. At the present time, none of the terminal blending products have been fully evaluated in the field.(1)

PERFORMANCE RECORD

The reported performance of crumb rubber in asphalt pavement has varied widely in different sections of the United States. Several states have had fairly extensive experience in using crumb rubber, some with the wet process. A summary of the experiences of selected states are presented in the next few paragraphs.

Over a 20-year period, starting in the early 1970's, over 3,000 lane-miles of streets in Phoenix, Arizona, have been seal coated using asphalt-rubber. In the early 1990's, the use of chip seals was discontinued in favor of 25 mm (1 in) thick asphalt-rubber hot mix overlays. Nearly 600 lane-miles of streets have been paved using hot mix overlay. Both the chip seals and the hot mix overlays have reportedly been effective in retarding the reflection of alligator cracks and shrinkage cracks less than 6.3 mm (1/4 in) in width. Compared with the chip seals, the 25 mm (1 in) thick asphalt-rubber hot mix overlay reportedly provides a more improved riding surface and a marked decrease in traffic noise.(3)

The California Department of Transportation (CalTrans) has been using rubber-modified asphalt concrete since 1978 and has constructed 17 wet process overlay installations. CalTrans has placed rubberized overlays over asphalt as well as concrete pavements using dense-graded, open-graded, and gap-graded asphalt concrete mixes. Since 1987, these CRM overlays have been placed at a reduced thickness compared with conventional overlays. Overall, CalTrans has reported that wet process overlays have usually out-performed thicker, dense-graded asphalt concrete by exhibiting less distress, requiring less maintenance, and being able to tolerate higher deflections.(4)

The Florida Department of Transportation (DOT) constructed three asphalt-rubber demonstration projects between March 1989 and September 1990. These projects involved one dense-graded and two open-graded friction courses using the Florida wet process technology. Although long-term performance has yet to be evaluated, data reviewed to date suggest that asphalt-rubber friction courses, particularly open-graded ores, will probably exhibit improved durability over conventional friction courses.(5)

The Kansas DOT constructed five projects using asphalt-rubber interlayers during the 1980's. On two of the projects, the interlayer was able to somewhat reduce reflective cracking. On the other three projects, there was little difference between the pavements with an interlayer and the control sections, and, in some cases, sections with the interlayer had more reflective cracking. On all five projects, the Kansas DOT concluded that the additional cost of an asphalt-rubber interlayer did not justify its use.(6)

The Minnesota DOT (MNDOT) has used CRM in asphalt paving on at least six different wet-process projects, beginning in 1979. The six projects involved two SAM's, three SAMI's, and one dense-graded overlay.(7) The MNDOT demonstration exhibited mixed results. Of the two stress- absorbing membranes, one was a success and one was a failure. The difference between success and failure depended on precoating of the aggregate chips that were used. Only minor problems were encountered with the installation of the three SAMI's. Reflective cracking was reduced, but not eliminated. Some improvement in crack reflection was observed in the asphalt-rubber dense-graded overlay, but the benefits were not deemed sufficient to offset the increase in cost.(7)

In Texas, crumb rubber has been used in asphalt paving mixtures in at least three different products dating back as far as 1976. The most frequent use of CRM in Texas has been in the construction of asphalt-rubber chip seals. Over 2,000 lane-miles of asphalt-rubber chip seals (SAM's) have been constructed in Texas. After many years of experience, Texas DOT personnel have concluded that SAM's exhibit improved resistance to alligator cracking and raveling, but that resistance to shrinkage cracking is not improved by the chip seals.(8)

Two other districts in Texas have experimented with the use of CRM in dense-graded asphalt-rubber hot mix overlays (wet process). Performance to date has been satisfactory for the two wet-process overlays.(8)

Since 1977, the Washington State DOT (WSDOT) has used three types of paving products from the wet process. Wet-process products include SAM's, SAMI's, and open-graded asphalt-rubber friction courses. WSDOT concluded that the performance of asphalt-rubber SAM's and SAMI's did not justify the added expense of their construction.(9) All five of the open-graded friction course installations are exhibiting good to very good performance, with the exception of one bridge deck overlay, which is showing some distress in the wheel path areas.(9)

In Ontario, Canada, three rubber-modified asphalt demonstration projects were evaluated in terms of pavement performance. The performance of the asphalt-rubber (wet process) projects was promising, insofar as the durability of these asphalt mixes appeared to be enhanced by the use of crumb rubber modifier.(10)

There have reportedly been six projects in the United States where asphalt pavements with CRM have been recycled. Roughly half of these projects were wet process and the other half were dry process. Apparently, there are no physical problems with recycling reclaimed asphalt pavement containing CRM as a portion of the aggregate in a new asphalt paving mix.

To summarize, the overall results of these performance investigations suggest the following:

Chip Seals (SAM's and SAMI's): Precoated chips must be used and are effective in reducing, but not eliminating, reflective cracking, especially in warmer climates.

Asphalt-Rubber Hot Mix Overlays: Improved performance was observed compared with conventional hot mix overlays in most climates. Dense-graded asphalt-rubber overlays may be effective at reduced thicknesses, compared with conventional overlays. Open-graded asphalt-rubber friction courses exhibit improved durability in warmer climates, compared with conventional friction courses.

Economic Comparisons: The overall consensus is that crumb rubber modified asphalt pavements may cost 1.5 to 2 times as much as conventional asphalt. Many states have questioned the cost effectiveness of CRM in hot mix asphalt.

MATERIAL PROCESSING REQUIREMENTS

Shredding

The initial step in the production of ground or granulated scrap tire rubber is shredding. Scrap tire rubber is delivered to rubber processing plants either as whole tires, cut tires (treads or sidewalls), or shredded tires, with shredded tires being the preferred alternative. As scrap, the rubber is processed, the particle sizing is reduced, steel belting and fiber reinforcing are separated and removed from the tire, and further size reduction is then accomplished.

Grinding and Granulation

Crumb rubber can be produced by one of three processes. The granulator process produces cubical, uniformly shaped particles ranging in size from 9.5 mm (3/8 in) down to 0.4 mm (No. 40 sieve), which is called granulated CRM. The crackermill process, which is the most commonly used, produces irregularly shaped torn particles sized from 4.75 mm (No. 4 sieve) to 0.42 mm (No. 40 sieve), referred to as ground CRM. The micro-mill process produces a very fine ground CRM, usually ranging from 0.42 mm (No. 40 sieve) down to as small as 0.075 mm (No. 200 sieve).(1) In the wet process, ground CRM is normally used with the McDonald technology and very fine ground CRM is used with the Florida technology.

ENGINEERING PROPERTIES

Some of the engineering properties that are of particular interest when rubber is incorporated in asphalt concrete (wet process) include asphalt viscosity, asphalt softening point, resilient modulus, permanent deformation, thermal cracking, and resistance to aging.

Viscosity: Adding crumb rubber to asphalt cement can dramatically increase the viscosity of the resultant asphalt-rubber binder. Various quantities of kerosene or other diluents can be used to adjust the viscosity. Viscosity increases can occur after the addition of diluents, but higher percentages of diluent usually result in lowered viscosity increases. Reaction temperatures also affect these relationships.(1) The benefit of increased viscosity of the asphalt-rubber binder is that additional binder can be used in the asphalt mix to reduce reflective cracking, stripping, and rutting, while improving the binder's response to temperature change and long-term durability, as well as its ability to adhere to the aggregate particles in the mix and to resist aging.

Softening Point: In addition to modifying binder viscosity, asphalt-rubber binders used in seal coats and hot mix asphalt show an increase in the softening point of the binder by 11°C (20°F) to 14°C (25°F), resulting in reduced rutting or shoving of the asphalt-rubber products at elevated temperatures. Modification of asphalt cement with ground tire rubber greatly increases binder elasticity compared with unmodified asphalt cement, thus providing asphalt-rubber pavement systems with increased resistance to deformation and cracking.

Resilient Modulus: Resilient modulus values for mixtures containing conventional aggregate and asphalt-rubber binder are generally lower than the resilient modulus values for similar mixtures in which conventional asphalt cement are used. The higher the temperature, the greater the difference between the resilient modulus of the conventional mix and the asphalt-rubber mix.(1)

Permanent Deformation: The permanent deformation properties of dense-graded asphalt-rubber mixtures are within the range of properties normally associated with conventional hot mix asphalt paving mixtures, although asphalt-rubber mixtures may be somewhat less resistant to permanent deformation.(1)

Thermal Cracking: Asphalt-rubber binders also exhibit reduced fracture temperatures compared with conventional asphalt cement, usually 5.5°C (10°F) to 8.3°C (15°F) lower, meaning that asphalt-rubber products are less brittle and more resistant to cracking at lower temperatures than conventional chip seals or hot mix asphalt paving. Isolated fatigue studies have also indicated greater resistance to low temperature thermal cracking. In summary, asphalt-rubber is more elastic than asphalt cement and remains elastic at lower temperatures.

Resistance to Aging: Laboratory data also indicate that asphalt-rubber mixtures are somewhat more resistant to aging than normal asphalt mixtures. Aging studies performed in asphalt-rubber binders placed in northern and central Arizona pavements indicate that asphalt-rubber binders have an increased resistance to hardening.(1) When crumb rubber is added to asphalt cement, fatigue life is improved.

DESIGN CONSIDERATIONS

Mix Design

Hot Mix Asphalt

Variations of standard Marshall and Hveem mix design procedures for hot mix asphalt have been used to design dense-graded hot mixes using crumb rubber. Marshall or Hveem stability tests and weight-volume parameters are the basis for each of these designs. Lower unit weight and Marshall or Hveem stability values are obtained using CRM asphalt mixtures, while flow and voids in mineral aggregate (VMA) values are increased compared with conventional mixes.(1) Mixing and compaction temperatures for CRM mixtures are often higher than those for conventional paving mixes. Depending on the mix design method, samples should be heated to 149°C (300°F) to 190°C (375° F) before compaction. Design air voids and aggregate gradation depend on the CRM content. Low CRM content in the wet process has little or no effect on the mix design. As a rule of thumb, if 20 percent crumb rubber is used in the binder, then the CRM binder content will be 20 percent greater than a conventional binder.(1)

Most wet processes use CRM particles ranging in size from 0.6 mm (No. 30 sieve) to 0.15 mm (No. 100 sieve). The CRM percentage by weight can range from 5 to 25 percent of the binder, but is typically 18 percent. The CRM and asphalt cement are blended at temperatures from

166°C (330°F) to 204°C (400°F). Reaction times may vary from 10 to 15 minutes up to 2 hours or more, with rubber type and gradation being the two most important variables.

Chip Seals

When asphalt-rubber is used in chip seals, the majority of SAM's and SAMI's have been designed and placed without predetermining the binder or the aggregate application rate. The most common approach has been to specify a fixed rate of asphalt-rubber binder, and then vary the aggregate application rate to achieve the desired product. The amount of asphalt-rubber binder suggested for use in chip seals is about 15 to 20 percent higher than that required for a typical asphalt cement binder without a temperature correction. The amount of asphalt-rubber binder suggested for use in interlayers is about 45 percent higher than that typically used in asphalt cement binder without a temperature correction.(1)

Structural Design

Conventional AASHTO design procedures for flexible pavements are typically used for pavements containing wet process CRM.(11) Most agencies elect to use the same thickness of asphalt-rubber pavement as the design thickness of a conventional hot mix asphalt pavement.

Since 1987, CalTrans has placed and evaluated the performance of at least eight different projects in which all, or at least a portion, of the asphalt-rubber pavement was constructed at a reduced thickness, compared with the conventional pavement. Thickness reductions ranged from 20 to 50 percent in dense-graded asphalt mixes. In the majority of these projects, the thinner asphalt-rubber mixes reportedly performed at least as well as the thicker, conventional dense-graded asphalt mixes.(4)

CONSTRUCTION PROCEDURES

There are a number of special construction procedures for hot mix asphalt pavements containing scrap tire rubber, as well as both chip-seal coats (SAM's) and interlayers (SAMI's).

Hot Mix Asphalt Pavements

The construction process normally used for hot mix asphalt pavements must be modified in order to produce a quality CRM hot mix. When using asphalt-rubber binders in either dense-graded, open-graded, or gap-graded mixtures, several changes in the normal construction process must be recognized.

Material Handling and Storage

Crumb rubber is most often shipped in 110 kg (50 lb) bags. The bags can be emptied directly into a reaction vessel for mixing with asphalt cement. The different viscosity of wet-process binders, particularly at the higher rubber content (in the 18 to 25 percent range), can cause problems with storage and/or pumping of the binder. Such problems are most likely to occur if the hot mix plant has been shut down for an extended time period.

Mixing

A blending and reacting unit should be added to ensure proper proportioning of the crumb rubber, base asphalt cement, and any other modifiers. Most wet processes use CRM particles ranging in size from 0.6 mm (No. 30 sieve) to 0.15 mm (No. 100 sieve). The CRM and asphalt cement are blended at temperatures from 166°C to 204°C (330° F to 400°F). Reaction times may vary from 10 to 15 minutes up to 2 hours or more, with rubber type and gradation being the two most important variables. The target temperature should be higher to allow for the greater viscosity of the binder at construction temperatures. Typical mixing temperatures for hot mix asphalt paving are from 149°C (300°F) to 177°C (350°F).

Placing and Compacting

Placement of hot mix asphalt paving material with wet-process CRM binder can be accomplished using standard paving machinery. Laydown temperature should be at least 121°C (250°F). Compaction must be completed as soon as possible.(1) Pneumatic tire rollers cannot be used because asphalt-rubber will build up on roller tires.(1)

Quality Control

To ensure proper quality control of the CRM binder, the crumb rubber particle size, the rate of addition of crumb rubber, the mixing temperature and the time of blending and reaction must all be carefully monitored.

It is recommended that compacted mixes be sampled according to AASHTO T168,(12) and tested for specific gravity in accordance with ASTM D2726(13) and in-place density in accordance with ASTM D2950.(14)

Chip-Seal Coats (SAM's) and Interlayers (SAMI's)

Construction of asphalt-rubber chip seals and interlayers (SAM's and SAMI's) is nearly identical to the construction of conventional chip seals. The major differences include the preparation of the asphalt-rubber binder and the use of specialized spray equipment.

Material Handling and Storage

Crumb rubber is most often shipped in 110 kg (50 lb) bags. The bags can be emptied directly into a reaction vessel for mixing with asphalt cement.

Mixing

Preparation of asphalt-rubber binder is done in blending vessels, which are often either special tanks or specialized binder distributors. They must be capable of heating the base asphalt cement, mixing the crumb rubber and the asphalt cement, and keeping the crumb rubber in suspension to avoid separation. When the crumb rubber is introduced into the asphalt cement, it swells and physical-chemical reactions occur that alter the properties of the base asphalt. Diluents of various types (such as kerosene) may be introduced to adjust the viscosity for spraying purposes.(1)

Placing and Compacting

Binder distribution equipment must be able to maintain the temperature of the binder at the desired level, circulate the binder to avoid separation of the crumb rubber and base asphalt, and discharge the binder in a uniform manner. Special pumps and nozzles are required to handle some asphalt-rubber binders.(1)

For chip-seal or interlayer applications, typical asphalt-rubber spray quantities are 2.5 L/m^2 (0.55 gal/yd^2) to 3.2 L/m^2 (0.70 gal/yd^2) for SAM's and 2.7 L/m^2 (0.60 gal/yd^2) to 3.6 L/m^2 (0.80 gal/yd^2) for SAMI's, compared with 1.6 L/m^2 (0.35 gal/yd^2) to 2.3 L/m^2 (0.50 gal/yd^2) for conventional chip seals. Typical aggregate application rates are in the range of 16 kg/m^2 (30 lb/yd^2) to 22 kg/m^2 (40 lb/yd^2) for SAM's and 8 kg/m^2 (15 lb/yd^2) to 14 kg/m^2 (25 lb/yd^2) for SAMI's, compared with conventional chip-seal application rates of 11 kg/m^2 (20 lb/yd^2) to 14 kg/m^2 (25 lb/yd^2).(1) As with all chip-seal construction, application of the chips should immediately follow application of the binder to ensure proper adhesion.

Quality Control

To ensure proper quality control of the CRM binder, the crumb rubber particle size, the rate of addition of crumb rubber, the mixing temperature, and the time of blending and reaction must all be carefully monitored.

Quality assurance of the chip seal will require that the particle sizing and application rate of the stone chips be closely inspected to ensure compliance with applicable specifications.

UNRESOLVED ISSUES

There are several unresolved issues relative to the use of crumb rubber as an asphalt cement modifier in asphalt concrete using the wet process.

Although only a limited amount of air emissions data from asphalt plants producing hot mix containing CRM are currently available, there is no evidence thus far that the use of an asphalt paving mix containing recycled crumb rubber exhibits any increased environmental impact when compared with that of emissions from the production of a conventional asphalt pavement.(10) Nevertheless, there is a need for additional studies on recyclability and worker health and safety issues for CRM asphalt paving mixes. Some of this work is presently underway and, as data become available, they should be incorporated into what is already known concerning these two aspects of using CRM in asphalt pavements.

Because of fluctuations in the performance of CRM asphalt mixes in different locations and/or climatic conditions, there is a need for more carefully controlled experimental field sections in different climatic regions throughout the United States in order to obtain more reliable performance data. Binder and mixture properties in these different regions need to be more accurately determined and documented. Performance records of these test sections may need to be monitored over a long period of time, at least 5 years and possibly as long as 30 years.(1)

Additional research is needed to define the properties of binders produced by the wet process. Desirable properties for chip seals, interlayers, and hot mix asphalt containing CRM need to be better defined using either existing or newly developed test methods.

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INTRODUCTION

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The dry process can be used for hot mix asphalt paving in dense-graded, open-graded, or gap-graded mixtures. It cannot be used in other asphalt paving applications, such as cold mix and chip seals or surface treatments. In the dry process, granulated or ground rubber and/or crumb rubber is used as a substitute for a small portion of the fine aggregate (usually 1 to 3 percent by weight of the total aggregate in the mix). The rubber particles are blended with the aggregate prior to the addition of the asphalt cement. When tire rubber is used as a portion of the aggregate in hot mix asphalt concrete, the resultant product is sometimes referred to as rubber-modified asphalt concrete (RUMAC).

The dry process used most frequently in the United States was originally developed in the late 1960's in Sweden and is marketed in this country under the trade name PlusRide by EnviroTire. The PlusRide technology is a patented process. In this process, from 1 to 3 percent granulated crumb rubber by weight of the total mix is added to the paving mix. The granulated rubber consists of rubber particles ranging in size from 4.2 mm (1/4 in) to 2.0 mm (No 10 sieve). The target air voids content of the asphalt mix is 2 to 4 percent, which is usually attained at an asphalt binder content in the 7.5 to 9 percent range.(1)

A generic dry process technology was developed in the late 1980's to early 1990's to produce dense-graded hot mixtures. This concept uses both coarse and fine crumb rubber to match aggregate gradings and to achieve improved binder modification. The crumb rubber may need a prereaction or pretreatment with a catalyst to achieve optimum particle swelling. In this system, rubber content does not exceed 2 percent by weight of total mixture for surface courses. Experimental pavement sections have been placed in Florida, New York, Oregon, and Ontario.(2)

The U.S. Army Corps of Engineers Cold Regions Research Engineering Laboratory (CRREL) investigated dry process CRM mixtures for disbonding ice on pavements. This research resulted in a recommendation to place field sections with mixtures containing crumb rubber particles larger than 4.75 mm (No. 4 sieve), with a top size of 9.5 mm (3/8 in). The technology is referred to as the chunk rubber process.(2) Marshall properties, resilient modulus, and ice removal tests have been performed in the laboratory with crumb rubber concentrations of 3, 6, and 12 percent by weight of aggregate. Laboratory wheel testing indicates that the higher rubber content mixes can potentially increase the incidence of ice cracking.(3) The chunk rubber process has not as yet been field evaluated.(2)

PERFORMANCE RECORD

The reported performance of rubber-modified asphalt concrete pavements has varied widely in different sections of the United States. The following paragraphs summarize the experiences of selected states with the dry process.

The California Department of Transportation (CalTrans) has constructed four projects using the PlusRide dry process technology. Some distress in the form of cracking or flushing in the wheel paths was observed in three of these projects, but overall, CalTrans has reported that two of the four dry process projects have out-performed conventional dense-graded asphalt, and a third project has performed comparably. A fourth project was not properly designed and required an overlay.(4)

The Minnesota Department of Transportation (MNDOT) has used the dry process in asphalt paving on a least two different projects, beginning in 1979. The two dry process projects were both PlusRide installations, using granulated crumb rubber and a gap-graded aggregate in an attempt to create a self de-icing pavement.(5) The two PlusRide sections have performed well, but have not shown benefits to offset the increased cost, and have not demonstrated any significant de-icing benefits.(5)

In New York, two experimental hot mix overlay projects using granulated rubber in the dry process were installed during 1989 to compare the construction characteristics and performance of rubber-modified asphalt concrete with a conventional top course paving mixture. All overlays were 37.5 mm (1-1/2 in) thick and placed over existing Portland cement concrete pavements, each with a leveling course of varying thickness. On both projects, the rubber-modified mixes consisted of PlusRide with 1, 2, or 3 percent granulated rubber aggregate.(6) After 3 years, the New York State DOT did not consider that these two overlay projects were either economical or successful.

One district in Texas has used rubber-modified hot mix asphalt (dry process). The mix raveled severely and the district was forced to place a chip seal over the mix within 3 months.(7)

Since 1977, the Washington State DOT (WSDOT) has undertaken a number of demonstrations with the dry process, using crumb rubber particles up to 6.3 mm (1/4 in) in size. The performance of the seven PlusRide sections has ranged from excellent to immediate failure.

Construction problems have plagued several of these installations. WSDOT concluded that, overall, PlusRide did not appear to provide improved performance.(8)

In Ontario, Canada, eight rubber-modified, dry process asphalt demonstration projects were evaluated in terms of pavement performance. They generally exhibited poor short-term performance.(9)

Performance of rubber-modified asphalt using the dry process has been mixed, with some early failures. Installations in service for several years generally show little improvement over conventional overlays. Little to no evidence of ice disbonding has been observed, except in laboratory tests.

MATERIAL PROCESSING REQUIREMENTS

Shredding

The initial step in the production of ground or granulated scrap tire rubber is shredding. Scrap tire rubber is delivered to rubber processing plants either as whole tires, cut tires (treads or sidewalls), or shredded tires, with shredded tires being the preferred alternative. As scrap tire rubber is processed, the particle sizing is reduced, steel belting and fiber reinforcing are separated and removed from the tire, and further size reduction is then accomplished.

Grinding

Rubber used in the dry process is ground rubber that is generally produced in a granulator process. This process further reduces shredded tire rubber and generates cubical, uniformly shaped particles ranging in size from 9.5 mm (3/8 in) down to a 0.42 mm (No. 40 sieve). However, the dry process can also use coarse crumb rubber from the crackermill process, which results in irregularly shaped particles ranging in size from 4.75 mm (No. 4 sieve) to 0.92 mm (No. 40 sieve).

ENGINEERING PROPERTIES

Some of the engineering properties of granulated or ground rubber that are of particular interest when used in asphalt concrete (dry process) include its gradation, particle shape, and reaction time.

Gradation: RUMAC paving mixes incorporate granulated or coarse crumb rubber particles that are most often processed to meet the gradation requirements shown in Table 16-1.(10)

Table 16-1. Gradation Requirements for RUMAC Mixes

Sieve Size	Percent Passing by Weight
6.3 mm (1/4 in)	100
4.75 mm (No. 4)	76 - 100
2.0 mm (No. 10)	28 - 42
0.85 mm (No. 20)	16 - 24

However, a chunk-rubber asphalt process developed for disbonding ice on pavements contains particles larger than 4.75 mm (No. 4 sieve) with a dominant size of 9.5 mm (3/8 in).

Particle Shape: Ground or granulated rubber particles produced from granulators, hammermills, or fine grinding machines have a cubical shape and a relatively low surface area. Coarse crumb rubber particles produced from the crackermill process have an irregularly torn shape and a relatively high surface area.

A cubical particle shape with a relatively low surface area is characteristic of conventional aggregate materials and is desirable for rubber particles that will function as a gap-graded aggregate in the dry process. Particles from the crackermill process that have an irregular shape with a relatively high surface area are more likely to react with asphalt cement at elevated temperatures and are better suited for use in the wet process. By limiting the time that the asphalt cement and crumb rubber particles are maintained at reaction temperatures and specifying a coarse granulated product with a relatively low surface area, the rubber particles can retain the physical shape and rigidity needed for use in the dry process. The smooth, sheared surfaces of ground or granulated rubber particles are also less reactive than the surfaces of the particles produced from the crackermill process.(1)

Reaction Time: In the PlusRide process, there is a relatively short reaction time when the rubber particles and aggregate are mixed with the asphalt cement, so the rubber particles do not have much opportunity to blend with the binder. There is a generic dry process that was developed in New York State, which uses coarse and fine crumb rubber prereacted with a catalyst to achieve optimum particle swelling, and which is added at a maximum of 2 percent by total mixture weight for surface courses.(2) In this process, the rubber particles may be able to react to a somewhat greater extent with the asphalt binder.

Some of the properties of RUMAC paving mixtures that are of interest include stability, resilient modulus, permanent deformation, and reflective cracking.

Stability: Paving mixtures produced by the dry process generally have reduced stability values, regardless of whether the Marshall or Hveem mix design procedures are used.

Resilient Modulus: Mixes containing granulated or crumb rubber typically have lower resilient modulus values than conventional hot mix asphalt. RUMAC paving mixes have been found to have resilient modulus values that are 10 to 20 percent higher than those of asphalt-rubber (wet process) paving mixes.

Permanent Deformation: Previous studies of granulated rubber paving mixtures indicate that resistance to permanent deformation of such mixes is reduced compared with that of conventional paving mixes. However, fatigue life is generally improved when crumb rubber is added by this process.(2)

Reflective Cracking: Addition of rubber aggregate can influence pavement performance in terms of reflective cracking. To achieve the benefits of delayed reflective cracking, a minimum rubber content must be added to the paving mix. This minimum rubber content is probably between 1 and 2 percent by weight of aggregate. The reaction between the rubber and the asphalt cement does not play a significant role in the enhancement of pavement performance in dry process mixes.(1)

DESIGN CONSIDERATIONS

Mix Design

Conventional Marshall and Hveem mix design methods have been used successfully for designing dense-graded mixtures with granulated rubber, but mixtures produced using the dry process typically do not follow the normal mix design procedures. Where stability is the primary design factor in most conventional mixes, the primary dry process design property is the percentage of air voids. The target air voids are between 2 and 4 percent.

During the laboratory mixing process, the granulated rubber is dry mixed with the aggregate before adding the asphalt cement. The asphalt concrete mixture is cooled for 1 hour after mixing. After compaction, the sample is cooled to room temperature. The air void content is determined after extrusion.(2)

Dry process paving mixes should be designed volumetrically to compensate for the lower specific gravity of the crumb rubber particles. Binder contents in dry process mixes are typically 10 to 20 percent higher than those of conventional mixes. Although the air voids content is the criterion for mix design, lower stability values and higher flow values can be expected, compared with conventional hot mix asphalt paving mixtures.(2)

Structural Design

The method used for the thickness design of rubber modified asphalt pavements, which incorporate between 1 and 3 percent by weight of granulated crumb rubber modifier (CRM) as fine aggregate, is essentially the same as that used for the thickness design of conventional hot mix asphalt pavements.(11) No adjustments are normally recommended in the design thickness of rubber modified asphalt pavements compared with that of conventional hot mix asphalt pavements.

When designing asphalt pavements using the structural number (SN), the resilient modulus at 20°C (68°F) is the material property that is considered. Resilient modulus values for 18 percent coarse (2.0 mm (No. 10 sieve)) and fine (0.2 mm (No. 80 sieve)) CRM by weight of asphalt binder in dense-graded mixtures were found to be lower than dense-graded control mixtures at three temperatures ranging from 5°C (41°F) to 40°C (104°F).(12) Since the structural layer coefficient of a pavement is directly proportional to resilient modulus, this would suggest that dry process CRM mixtures should have a lower structural layer coefficient and require some increase in thickness.

CONSTRUCTION PROCEDURES

Material Handling and Storage

Both batch and drum-dryer plants have been used to produce RUMAC. The reclaimed granulated rubber is usually packed and stored in 110 kg (50 lb) plastic bags. Additional manual labor and conveying equipment, such as work platforms, are needed in order to introduce the granulated rubber into the paving mix, regardless of the type of mixing plant used. A batch plant has a quality control advantage over a drum-dryer plant because the number of preweighed bags of granulated rubber can be easily counted prior to their addition into each batch. The bags may be opened and the granulated rubber placed on a conveyor, or the bags may be put into the pugmill or cold feed bin if low melting point plastic bags are used.

Control of the feeding of granulated rubber is necessary because the correct rubber content is critical to the performance of the paving mix when using the dry process. Such control is more difficult to maintain in a drum-dryer system, due to the nature of the feed operation. Some drum-dryer plants have used recycled asphalt concrete hoppers to feed the granulated rubber, although a number of agencies recommend that the rubber be introduced into the mix through a center feed system. The process can be automated by the addition of a conveyor and hopper, plus scales to accurately proportion the granulated rubber.

Mixing

For both batch and drum-dryer plants the addition of rubber normally requires that the mixing time and temperature be increased. Batch plants require a dry mix cycle to ensure that the heated aggregate is mixed with the crumb rubber before the asphalt cement application. Mixtures should be produced at 149°C to 177°C (300°F to 350°F).

Placing and Compacting

Laydown temperature should be at least 121°C (250°F). A finishing roller must continue to compact the mixture until it cools below 60°C (140°F). Otherwise, the continuing reaction between the asphalt and the crumb rubber at elevated temperatures will cause the mixture to swell.(2) Continued compaction until the mixture cools below 60°C (140°F) serves to contain the expansive pressure of the compressed rubber.

Quality Control

Parameters that must be monitored during mixing for dry process mixes include rubber gradation, rubber percent of total mixture weight, rubber prereaction or pretreatment, and time of plant mixing. Since dry process binder systems are partially reacted with the rubber, it is not possible to directly determine the properties of the binders.

It is recommended that compacted mixes be sampled according to AASHTO T168,(13) and tested for specific gravity in accordance with ASTM D2726(14) and in-place density in accordance with ASTM D2950.(15)

UNRESOLVED ISSUES

There are several unresolved issues relative to the use of rubber as fine aggregate in asphalt concrete using the dry process. The overwhelming majority of projects and data concerning crumb rubber use in asphalt paving are from installations using the wet process. As a result, there is a lack of field data to evaluate performance.

There have been six projects in the United States where asphalt pavements with CRM have been recycled. Roughly half of these projects were wet process and the other half were dry process. Apparently, there are no physical problems with recycling reclaimed asphalt pavement containing CRM as a portion of the aggregate in a new asphalt paving mix; however, additional field trials are needed.

Although only a limited amount of air emissions data from asphalt plants producing hot mix containing CRM are currently available, there is no evidence thus far that the use of an asphalt paving mix containing recycled crumb rubber exhibits any increased environmental impact when compared with that of emissions from the production of a conventional asphalt pavement.(16) Air emission data from a project in New Jersey in 1992 where dry process CRM was recycled as 20 percent of new aggregate in a drum mix plant showed that current air quality standards were not exceeded during the recycling.(16) Nevertheless, there is a need for additional studies on recyclability and worker health and safety issues for CRM asphalt paving mixes. Some of this work is presently underway and, as data become available, they should be incorporated into what is already known concerning these two aspects of using CRM in asphalt pavements.

Because of fluctuations in the performance of CRM asphalt mixes in different locations and/or climatic conditions, there is a need for more carefully controlled experimental field sections in different climatic regions throughout the United States in order to obtain more reliable performance data. Binder and mixture properties in these different regions need to be more accurately determined and documented. Performance records of these test sections may need to be monitored over a long period of time, at least 5 years and possibly as long as 30 years.(2)

Additional research is needed to define the properties of binders produced by the dry process. Desirable properties for dry process hot mix asphalt mixtures need to be better defined.

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INTRODUCTION

Shredding of scrap tires produces chunks of rubber ranging in size from large shreds to smaller chips. Tire shreds and tire chips have both been used as lightweight fill materials for roadway embankments and backfills behind retaining walls. The shreds or chips can both be used by themselves or blended with soil. Tire shreds normally range in size from 305 mm (12 in) to 76 mm (3 in), while tire chips are usually sized from a maximum of 76 mm (3 in) down to a minimum of 12 mm (1/2 in). Embankments containing tire shreds or chips are constructed by completely surrounding the shreds or chips with a geotextile fabric and placing at least 0.9 m (3 ft) of natural soil between the top of the scrap tires and the roadway.

PERFORMANCE RECORD

At least 15 states have utilized scrap tire shreds or chips as a lightweight fill material for the construction of embankments or backfills. Some projects have used tire shreds or chips as embankment material, while other projects have blended tire chips with soil. The states that have used tire shreds or chips in embankments are California, Colorado, Indiana, Maine, Minnesota, New Jersey, North Carolina, Oregon, Pennsylvania, South Carolina, Vermont, Virginia, Washington, Wisconsin, and Wyoming. The largest known use to date is in Oregon, where 580,000 scrap tires were shredded and used in a landslide correction project. In Colorado, between 400,000 and 450,000 scrap tires were used to construct an embankment containing tire chips on a section of interstate highway.(1) To date, more than 70 successful projects have been constructed on state, local, or private roads.(2)

Aside from problems with puncturing of rubber tires on haul vehicles by the exposed steel in tire chips or shreds, there have been no other construction-related problems on scrap tire embankment projects. Adequate compaction, which is always a prime concern on any embankment project, is of even greater concern on a tire shred or chip embankment project, where it is known that some consolidation will occur. Some cracking of the roadway above a tire shred or chip embankment is possible because of long-term settlement or differential settlement.

Although at least 15 states have had scrap tire embankment projects, only six states (North Carolina, Oregon, Vermont, Virginia, Wisconsin, and Maine) have prepared specifications or some provisions for this use.(1)

Scrap tire embankments that have been constructed to date have remained structurally stable; however in 1995, three shredded tire projects experienced combustion problems. Two of these projects were located in Washington State. The other project was located in Colorado. Preliminary assessments indicate that the combustion process may have been initiated by heat released either by the presence of organic soils and microbial degradation, the oxidation of exposed steel wires, or microbes consuming liquid petroleum products that could have been spilled on the tire shreds during construction.(2) The presence of both sufficient air and crumb rubber particles in the embankment may have played a role in the process. The crumb rubber in the presence of air may have ignited when exposed to the heat generated in the embankment, initiating the combustion process.

The use of tire shreds or tire chips for the construction of embankments provides a number of advantages. The most obvious advantage is that of reduced unit weight, which is especially beneficial in situations where an embankment is to be constructed over an area with low bearing support. In addition to being a lightweight fill material, tire shreds or tire chips offer good thermal characteristics in resisting frost penetration and have good drainage characteristics, being as permeable as a coarse granular soil. Embankments present an excellent opportunity to utilize large volumes of scrap tires from one location and, under the proper logistical circumstances, can be a very economical alternative to imported earth borrow.(3)

MATERIAL PROCESSING REQUIREMENTS

Shredding

The size and shape of tire shreds or chips from tire shredding can vary depending on the type of shredding machinery used. Tire shreds have a wide range of sizes, from 76 mm (3 in) up to 305 mm (12 in), which is ordinarily the largest size recommended. Chip sizes normally range from 12 mm (1/2 in) up to 76 mm (3 in). Usually, tire shreds are irregular in shape with the smaller dimension being the size specified by the manufacturer and the larger dimension possibly being two or more times as much. The chips, on the other hand, are cubical in shape. Some shreds or chips may have pieces of steel belt exposed along the edges. To minimize potential compaction problems (i.e., to reduce void space) it may be desirable to use smaller size tire chips of 50 mm (2 in) or less.(4)

ENGINEERING PROPERTIES

Some of the properties of tire chips or shreds that are of particular interest when they are planned for use in an embankment or backfill include particle size and shape, specific gravity, compacted unit weight, shear strength, compressibility, permeability, and combustibility. Due to the differences between tire shreds or chips and stone or soil-like embankment materials, physical characterization of tire shreds or chips represents a specific challenge to the tire user.

Particle Size and Shape: Tire chips are normally somewhat uniformly sized and will most often range in size from 25 mm (1 in) to 50 mm (2 in). Tire shreds are more well-graded, usually ranging from 101 mm (4 in) to 202 mm (8 in) in size. Some particles may be 305 mm (12 in) or even larger, including some strip-shaped pieces. The most unusual properties of tire shreds are their flat and somewhat irregular particle shape and their relatively low unit weight. The flat shreds, especially the larger sizes, tend to lay on top of one another and develop some degree of particle interlock. They also tend to be oriented parallel to the horizontal shear plane.

Particle size distribution can be determined by performing a standard sieve analysis using the procedures of ASTM D422. No modification of the standard test method is required, except that tire shreds larger than 76 mm (3 in) cannot be screened through standard sieves.

A limited amount of geotechnical analysis has been performed on different sizes of tire chips. Grain size analyses have indicated that the tire chips can be classified as a well-graded, coarse-grained material, similar to an A-1-b sand and gravel (AASHTO M145) or as an SW well-graded sand with gravel (ASTM D2487).(4)

Specific Gravity: The specific gravity of tire chips is expected to be in the 1.1 to 1.3 range, with higher specific gravity values for chips containing steel belts.(5)

Compacted Unit Weight: Depending on the size of the chips, compacted unit weights can range from as low as 322 kg/m^3 (20 lb/ft^3) to as high as 725 kg/m^3 (45 lb/ft^3).(4) Tire shreds or chips have a maximum density that is approximately one-third to one-fourth that of typical earthen fill material. The coarser the size of the scrap tire particle, the lower the compacted unit weight.

Determination of compacted density of air-dried tire chips is best made by an adaptation of ASTM D1557 (Modified Proctor test). A 254 mm (10 in) diameter by 254 mm (10 in) high mold is recommended instead of the usual 101 mm (4 in) diameter high mold. Since the level of energy applied is not critical, 60 percent of standard Proctor compaction effort is recommended.(6)

Shear Strength: Limited direct shear testing of tire chips has been performed using a specially made large-scale direct shear testing apparatus. The friction angle of tire chips from these tests ranged from 19° to 25°. Cohesion values range from 7.6 kPa (160 lb/ft^2) to 11.5 kPa (240 lb/ft^2), although significant deformation was required to develop cohesion. Tire chips with a greater amount of exposed steel belts tend to have a higher angle of internal friction.(5) Typical granular soils have friction angles between 30° and 40° with little apparent cohesion.

The shear strength of tire chips can be evaluated by performing direct shear tests using a 305 mm (12 in) square shear box. This is a modification of ASTM D3080 and is applicable to the testing of 76 mm (3 in) maximum size tire chips.(6)

Compressibility: Tire shreds or chips are much more compressible during the initial stages of loading than conventional soils. Subsequent loading cycles normally result in significantly less compressibility of the tire shreds or chips. Higher amounts of exposed steel belts appear to result in higher compressibility, especially during the first loading cycle, probably because of less rebound.(5)

Compressibility analysis of tire chips indicates that the Young's modulus of tire chips is 2 to 3 orders of magnitude less than the modulus of granular soil. The values of Young's modulus for tire chips range from 770 kPa (112 lb/in^2) to 1250 kPa (181 lb/in^2). Therefore, at least 0.9 m (3 ft) of conventional soil is required to be placed on top of a layer of tire chips in order to prevent or minimize surface deflections.

Compressibility can be analyzed by applying a vertical load to compacted tire chips (5 layers, 60% of standard Proctor effort) within a 305 mm (12 in) diameter by 305 mm (12 in) long schedule 40 PVC pipe equipped with horizontal and vertical strain gauges. The strain gauges record horizontal and vertical stress and strain readings at 10 second intervals. Readings are plotted on stress-strain curves. The slopes of these curves are indicative of the compressibility of tire chips and the coefficient of lateral earth pressure.

Permeability: The coefficient of permeability of tire chips was found to range from 1.5 to 15 cm/sec, depending on their void ratio. This is equivalent to the permeability of a clean gravel soil.(5)

Permeability testing can be accomplished using a 305 mm (12 in) diameter by 0.96 meter (38 in) long PVC pipe and following the constant head testing procedures of the California Department of Transportation. A 38 mm (1.5 in) diameter water inlet was fixed to the center of the end cap. A 101 mm (4 in) wide by 50 mm (2 in) deep slot was cut into the top of the PVC pipe to allow water to flow out the top of the apparatus. The initial length of the tire chip sample is about 600 mm (24 in).(5)

Combustibility: Although scrap tire particles (shreds or chips) are not in and of themselves capable of spontaneous combustion, it does appear to be possible that, under certain circumstances, an initial exothermic reaction may occur within a tire shred or tire chip embankment or backfill that could eventually raise the temperature within the fill to a point where ignition could possibly occur.

DESIGN CONSIDERATIONS

Mix Design

Tire chips can be mixed or blended with soil. As the percentage of soil is increased, the unit weight of the blend increases. To simplify blending in the field, mix ratios are usually prepared on a volumetric basis. A maximum 50:50 tire chip to soil ratio is suggested so that tire chip usage is not reduced too greatly. However, if the unit weight of the fill is not a concern, then even small percentages (10 to 25 percent) of tire chips can be blended into the soil. This could improve the compactibility of the fill.

Structural Design

Since tire chips and shreds are unlike conventional materials, special empirical design procedures must be considered. The principal design considerations include shred or chip containment, shred or chip particle size distribution, particle shape, type of belt, compacted density of the tire chips, and whether soil will be mixed with the chips.

To contain tire shreds or chips, a geotextile fabric should be placed beneath the shreds or chips and wrapped around and above them. The geotextile must completely enclose the tire shreds or chips in order to provide the necessary containment. Although smaller size tire chips have an angle of repose of around 50°, 2:1 side slopes (horizontal to vertical) are recommended.(4) At least a 0.9 m (3 ft) soil cover should be placed between the top of the enclosed tire chip fill and the base of a pavement to reduce deflections and to minimize differential settlement within the fill. If heavy wheel loadings are anticipated, an additional 0.6 m (2 ft) soil surcharge can be placed, which can be removed following appropriate settlement prior to pavement construction.

A major concern in the use of tire shreds or chips in an embankment are the comparatively large settlements (about 10 to 15 percent of the height of the tire layer) that have been observed in various field studies. There is little information available on the tolerable settlements of highway embankments. Postconstruction settlements of 0.3 to 0.6 m (1 to 2 ft) over the life of an embankment may be considered tolerable provided they are reasonably uniform, do not occur adjacent to a pile-supported structure, and occur slowly over a long period of time. The detrimental effects of settlements in this range can be reduced by using flexible pavement over scrap tire fills, by inducing some of the postconstruction settlement during construction by placing a thicker soil cap or a surcharge earth loading over the embankment, or by using stage construction.(7)

Another possible means of mitigating scrap tire embankment settlements is to use a rubber-soil mix to construct the embankment, instead of using tire shreds or tire chips alone. It has been found that a ratio of about 40 percent tire chips by weight of soil may be an optimum value for the quantity of chips in a rubber-soil mix, although this may vary depending on the size of the tire chips and the type of soil. The optimum ratio of tire chips to soil is likely to yield a compacted dry unit weight of rubber-soil mix that is roughly two-thirds the dry unit weight of soil alone. Data on the stress-strain and strength behavior of rubber-soil mixtures are not widely available, but are necessary for the design and prediction of performance of scrap tire embankments that contain such mixtures.(7)

CONSTRUCTION PROCEDURES

Material Handling

At the tire processing facility, the number of tires to be processed into shreds or chips is directly related to the intended volume of the tire chip portion of the embankment. It is estimated that every cubic yard of volume will require about 75 automobile tires that have been shredded into shreds or chips and compacted into an embankment.(5)

Site Preparation

The site of the embankment should be prepared in essentially the same manner as though common earth were being used for fill material. If there is a high water table or swampy area that will be at the base of the embankment, it may be advisable to construct a drainage blanket. If there is a natural flow of runoff through the area where the embankment is to be constructed, provisions should be made to pipe the runoff beneath the embankment.

Mixing

When tire shreds or chips are to be blended or mixed with soil, the mixing should be performed volumetrically, using bucket loads from a front end loader and blending the materials together as well as possible with the bucket. As another option to the mixing of tire shreds or chips and soil, alternate layers of the tire shreds or chips and the soil can be constructed.

Placing and Compaction

Once the base of the embankment has been prepared, the geotextile that will enclose the tire chips should be placed. A nonwoven geotextile fabric is recommended. Sufficient length should be provided to completely wrap around the tire chips once they have been placed and compacted.

Tire chips should be spread across a geotextile blanket using a tracked bulldozer. A minimum 0.6 m (2 ft) layer or lift should be spread out over the geotextile. A recommended maximum 1 m (3 ft) lift thickness can still be spread and compacted. Compaction may be achieved by at least three passes of the tracked bulldozer over the layer of tire chips.(8) The chip particles align themselves with each other and settle fairly readily. The weight of the bulldozer passing over the tire chips is enough to readily compact the layer of chips. For larger chips or thicker layers of chips, as many as 15 passes of a bulldozer may be required to achieve compaction.(9)

Once the bulldozer is able to pass over a layer of tire chips with little to no noticeable deflection or movement under the tracks of the bulldozer, the next layer or lift of tire chips can be placed. There is really no practical method at this time for performing an in-place density test on a layer of compacted tire chips. The best way to ensure that the layer has been sufficiently compacted before placement of the next layer is to continue passes of the bulldozer over the tire chips until there is no more movement of the tire chips when the bulldozer passes over them.

The top layer of a tire chip embankment should be kept at least 1 m (3 ft) below the base or subbase layer of the pavement that will be on top of the embankment. Each layer of a tire chip embankment must be fully compacted before the next layer is placed. When the top layer of tire chips has been fully compacted, the sides and top of the tire chips should be fully wrapped and enclosed by the geotextile.

A minimum of 0.9 m (3 ft) of compacted soil (preferably granular soil) should be placed on top of the geotextile and tire chips. The soil should be compacted in thinner layers 15 mm (6 in) to 305 mm (12 in) in thickness. The tire chip embankment will experience further deflection during placement and compaction of the soil cover.

At least 0.6 m (2 ft) of soil should also be placed on the side slopes of the embankment to cover the geotextile wrap. The soil on the slopes should be compacted to the extent possible, covered with topsoil, and seeded to establish erosion control protection. The additional soil cover on the side slopes will also help minimize the potential of exothermic reactions occurring within the scrap tire embankment.

Quality Control

There is little in the way of field quality control testing that can be done during the construction of a tire chip embankment, other than to very closely inspect the compaction of each tire chip layer to ensure that there is very little to no movement under the passage of a bulldozer before proceeding to install the next layer of chips. However, the overall settlement or deflection of a tire chip embankment can be monitored over time by the installation of settlement plates or platforms, slope indicator devices, and bench marks along the slopes of the embankment and within or adjacent to the roadway. Periodic readings should be taken using these devices in order to keep track of the extent and rate of settlement and to compare actual settlements with predicted settlements.

To minimize the potential for an exothermic reaction to occur within a portion of a tire shred or tire chip embankment or backfill, a number of preventive measures should be taken. Contact with oxygen within the scrap tire fill should be reduced as much as possible by covering the fill with at least 1.3 m (4 ft) of well-compacted natural nonorganic soil. The amount of exposed steel belts at the edges of the shred or chip particles should be limited by using magnetic separation or using large-size particles. No crumb rubber should be allowed to be used in a scrap tire fill. Tire shreds or chips that have been contaminated by liquid petroleum products should be removed from a scrap tire fill and disposed of in an environmentally acceptable manner. There should be no contact between tire shreds or chips and either topsoil or fertilizer.(2)

UNRESOLVED ISSUES

There are several unresolved issues pertaining to the preparation and use of shredded scrap tires in fills and embankments. The first and most pressing unresolved issue is to determine the cause or causes of the exothermic reactions that resulted in three scrap tire embankment fires that occurred during 1995. Other tire shred or tire chip embankment projects, especially the thick fills, including those that have caught on fire, should be more closely monitored, possibly by installing temperature probes and gas sampling wells. Gas from such wells should be periodically sampled and analyzed for oxygen level, hydrogen sulfide, carbon dioxide, carbon monoxide, and hydrocarbons. The pH of any water leaching from scrap tire fills should be measured. Laboratory investigations should also be undertaken under varying conditions and temperatures to pinpoint under which conditions exothermic reactions may be initiated.(2)

One of the principal questions concerning such use of shredded scrap tires is that of an optimum particle size and shape of the tire shreds or chips. More information is needed on the basic types of tire shredding machinery currently in use and their effect on particle shape and size. The effects of mixing or blending various size shreds or chips within an embankment also need to be further evaluated in terms of resultant engineering properties, optimum gradation of shreds or chips, compaction and settlement behavior, as well as potential combustibility.

Another consideration that warrants further investigation concerns the blending of soil and tire chips or shreds. Among the variables that need to be further investigated are the effect of various proportions of tire chips and soil on the engineering properties of the resultant composites, especially the bulk density and compaction characteristics. The type of soil is another variable that will influence the bulk density and compaction characteristics of the tire chip-soil blends. If possible, optimum proportions of tire chips and soil should be identified for different tire particle sizes and/or soil types.

There is currently very little in the way of field quality control testing that is now being done during the construction of a tire chip or tire shred embankment, other than visual inspection of movement or settlement of the tire chip or shred layers under compaction machinery. Some rational methods of in-place density and/or compaction percentage measurement need to be developed and field tested to help minimize settlement of tire chip or tire shred fills under traffic loading.

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ORIGIN

Sewage sludge ash is the by-product produced during the combustion of dewatered sewage sludge in an incinerator. Sewage sludge ash is primarily a silty material with some sand-size particles. The specific size range and properties of the sludge ash depend to a great extent on the type of incineration system and the chemical additives introduced in the wastewater treatment process.

At present, two major incineration systems, multiple hearth and fluidized bed, are employed in the United States. Approximately 80 percent of the incinerators used in the United States are multiple hearth incinerators.

The multiple hearth incinerator is a circular steel furnace that contains a number of solid refractory hearths and a central rotating shaft. Rabble arms that are designed to slowly rake the sludge on the hearth are attached to the rotating shaft. Dewatered sludge (approximately 20 percent solids) enters at the top and proceeds downward through the furnace from hearth to hearth, pushed along by the rabble arms. Cooling air is blown through the central column and hollow rabble arms to prevent overheating. The spent cooling air with its elevated temperature is usually recirculated and used as combustion air to save energy. Flue gases are typically routed to a wet scrubber for air pollution control. The particulates collected in the wet scrubber are usually diverted back into the sewage plant.(1)

Fluidized bed incinerators consist of a vertical cylindrical vessel with a grid in the lower sections to support a bed of sand. Dewatered sludge is injected into the lower section of the vessel above the sand bed and combustion air flows upward and fluidizes the mixture of hot sand and sludge. Supplemental fuel can be supplied by burning above and below the grid if the heating value of the sludge and its moisture content are insufficient to support combustion.(1)

Figure 17-1 shows a simplified flow diagram of a sludge incinerator. The complete system includes sludge pretreatment operations such as sludge thickening (sedimentation) and sludge dewatering (vacuum filter, centrifuge, or filter press), followed by incineration, air pollution control, and ash handling. Sludge dewatering may involve the addition of ferrous chloride, lime, or organic polymers to enhance the dewatering process. Auxiliary fuel is normally needed to maintain the combustion process.(2) The quantity of auxiliary fuel required depends on the heating value of the sludge solids and, primarily, on the moisture content of the incoming feed sludge.

Operating temperatures can vary, depending on the type of furnace, but can be expected to range from approximately 650°C (1200°F) to 980°C (1800°F) in the incinerator combustion zone. High operating temperatures above 900°C (1650°F) can result in partial fusion of ash particles

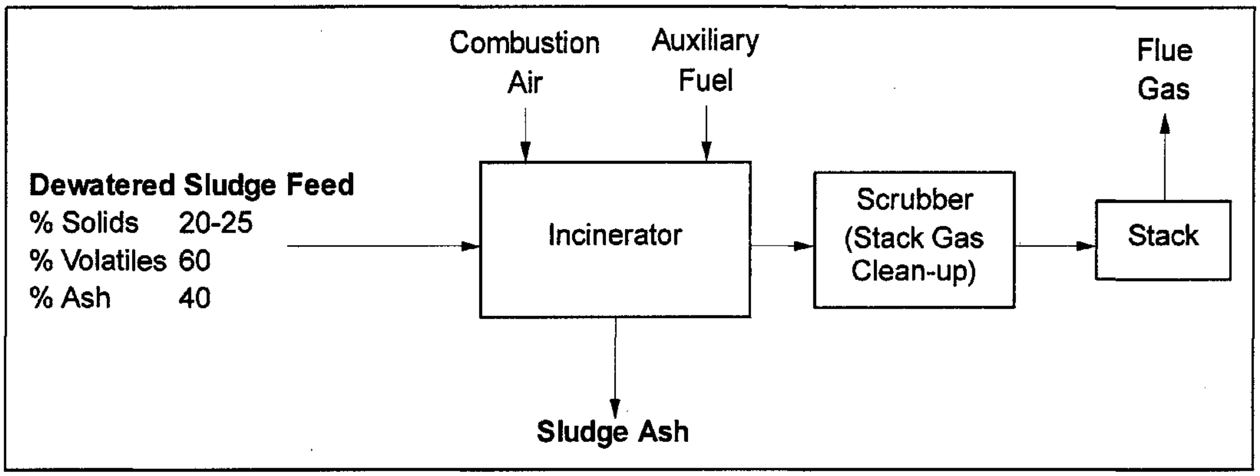

Figure 17-1: Simplified sludge incinerator flow diagram.

and the formation of clinkers, which end up in the ash stream. Lime may also be added to reduce the slagging of sludge during incineration.(3)

Incineration of sewage sludge (dewatered to approximately 20 percent solids) reduces the weight of feed sludge requiring disposal by approximately 85 percent. There are approximately 170 municipal sewage treatment plant incinerators in the United States, processing approximately 20 percent of the nation's sludge, and producing between 0.45 million and 0.9 million metric tons (0.5 and 1.0 million tons) of sludge ash on an annual basis.(4)

CURRENT MANAGEMENT OPTIONS

Recycling

Sludge ash has been previously used as a raw material in Portland cement concrete production, as aggregate in flowable fill, as mineral filler in asphalt paving mixes, and as a soil conditioner mixed with lime and sewage sludge.(5,6) Some California sludge ash with high copper content has reportedly been sent to an Arizona smelter for copper recovery.(7) Sludge ash has also been proposed as a substitute lightweight aggregate product, produced by firing sludge ash or a mixture of sludge ash and clay at elevated or sintering temperatures. Other potential uses that have been reported include the use of ash in brick manufacturing(8) and as a sludge dewatering aid in wastewater treatment systems.(9)

Applications that could potentially make use of sewage sludge ash in highway construction include the use of ash as part of a flowable fill for backfilling trenches or as a substitute aggregate material or mineral filler additive in hot mix asphalt.(6,10,11)

Disposal

Most of the sludge ash generated in the United States is presently landfilled.

MARKET SOURCES

Sludge ash can be obtained directly from municipal wastewater treatment facilities with sludge incinerators or from private companies responsible for the disposal of the sludge ash. Due to the relatively small quantities of sludge ash generated, provisions for ash storage will be required to accumulate sufficient amounts for most applications.

Sludge ash properties (chemical) depend on the nature of the wastewater and the chemicals used in the treatment and sludge handling and incineration process. Since sludge is almost always dewatered prior to combustion, pretreatment of the sludge to enhance the dewatering process may include the addition of ferrous salts, lime, organics, and polymers. Ash produced at treatment plants that introduce ferrous salts or lime for sludge conditioning and dewatering contain significantly higher quantities of ferrous and calcium, respectively, than plants that do not. The pH of sludge ash can vary between values 6 and 12, but sludge ash is generally alkaline.

Sludge ash from multiple hearth incinerators will usually consist primarily of silty material mixed with some larger sand-sized particles. The formation of larger particles is normally the result of higher operating temperatures and the formation of clinkers. Fluidized bed furnaces produce only a very fine (silt-sized) ash.

HIGHWAY USES AND PROCESSING REQUIREMENTS

Asphalt Concrete Aggregate and Mineral Filler

Sludge ash has been used in asphalt paving mixes (6,10,11) to replace both fine aggregate and mineral filler size fractions in the mix. A number of test pavements have been successfully placed in Minnesota.(6)

Sludge ash can also be vitrified to produce a frit for use as an aggregate substitute material. A plant operated in New York State for approximately 3 years, but closed in 1995. It produced a vitrified frit-like product that was approved by the New York State Department of Transportation for use as fine aggregate substitute in paving mixes.(12)

Flowable Fill Aggregate

Sludge ash has reportedly been used as a fine aggregate substitute in flowable fill applications, although there is no documented use of sludge ash in this application.(6)

MATERIAL PROPERTIES

Physical Properties

Table 17-1 presents physical property characterization data for sludge ash from several sources. Sludge ash is a silty-sandy material. A relatively large fraction of the particles (up to 90 percent in some ashes) are less than 0.075 mm (No. 200 sieve) in size. Sludge ash has a relatively low organic and moisture content. Permeability and bulk specific gravity properties are not unlike those of a natural inorganic silt. Sludge ash is a nonplastic material.

Chemical Properties

Sludge ash consists primarily of silica, iron and calcium. The composition of the ash can vary significantly as previously noted, and depends in great part on the additives introduced in the sludge conditioning operation. There are no specific data available relative to the pozzolanic or cementitious properties of sludge ash, but sludge ash is not expected to exhibit any measurable pozzolanic or cementitious activity. Table 17-2 lists the range of major elemental concentrations present in sludge ash reported from two sources.

Trace metal concentrations (e.g., lead, cadmium, zinc, copper) found in sludge ash are typically higher than concentrations found in natural fillers or aggregate. This has resulted in some reluctance to use this material; however, recent investigations (leaching tests) suggest that these trace metal concentrations are not excessive and do not pose any measurable leaching problem. (See references 6,11,13,14.)

Table 17-1. Typical physical properties of sewage sludge ash.

Property	Values			
Gradation (% passing)	Wegman(10)	Khanbiluardi(11)	Waste Commission(6)	Gray(15)
4.76 mm (No. 4 sieve)	99	100	100	100
2.38 mm (No. 8 sieve)	99	98	100	100
2.00 mm (No. 10 sieve)	–	–	100	–
0.85 mm (No. 20 sieve)	–	–	100	–
0.42 mm (No. 40 sieve)	99	73	98	–
0.21 mm (No. 80 sieve)	–	–	83	–
0.149 mm (No. 100 sieve)	85	53	–	–
0.074 mm (No. 200 sieve)	66	38	56	47 - 93
– (0.0902 mm)	10 - 13	–	–	2-13
0.02 mm	–	–	20	–
0.005 mm	–	–	12	–
0.001 mm	–	–	2	–
Loss on Ignition (%)	1.4(10)			
Moisture Content (% by Total Weight)	0.28(11)			
Absorption (%)	1.6(6)			
Specific Gravity	2.60(10) 2.61(6) 2.44 - 2.96(15) 2.39 - 2.99(2)			
Bulk Specific Gravity	1.82(11) 1.27 - 1.48(2)			
Plasticity Index	Nonplastic(10)			
Permeability (ASTM D2434 - cm/sec)	4×10^{-4} (11) 1×10^{-4} - 4×10^{-4} (6)			

Table 17-2. Typical range of elemental concentrations in sewage sludge ash.

		Concentration %			
Elemental Element	**Oxide**	**Reported as Elemental Concentration$^{(2)}$**	**Reported as Elemental Concentration$^{(6)}$**	**Reported as Oxides$^{(10,16)}$**	**Reported as Oxides$^{(15)}$**
Silicon (Si)	(SiO_2)	5.6 - 25.7	20	27.0	14.4 - 57.7
Calcium (Ca)	(CaO)	1.4 - 42.9	8	21.0	8.9 - 36.9
Ferrous (Fe)	Fe_2O_3)	1.0 - 16.4	4	8.2	2.6 - 24.4
Aluminum (Al)	(Al_2O_3)	1.1 - 8.5	7	14.4	4.6 - 22.1
Magnesium (Mg)	(MgO)	0.6 - 1.9	2	3.2	0.8 - 2.2
Sodium (Na)	(Na_2O)	0.1 - 0.8	0.3	0.5	0.1 - 0.7
Potassium (K)	(K_2O)	0.3 - 1.6	0.5	0.6	0.07 - 0.7
Phosphorus (P)	(P_2O_5)	1.2 - 4.4	6	20.2	3.9 - 15.4
Sulfur (S)	(SO_3)	0.3 - 1.2	–	0.9	0.01 - 3.4
Carbon (C)	–	0.6 - 2.2	–	–	–

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INTRODUCTION

Sewage sludge ash can be used as a mineral filler substitute or as a portion of the fine aggregate in hot mix asphalt paving. The introduction of sewage sludge ash at levels of approximately 2 to 5 percent by weight of aggregate has been shown to produce mix design properties that are comparable to those of mixes containing conventional fillers such as hydrated lime and stone dust.

PERFORMANCE RECORD

During the past 15 years a number of laboratory investigations have been undertaken, and field demonstration pavements have been constructed, using sludge ash that has been incorporated into hot mix asphalt as either a mineral filler or as fine aggregate substitute. Although data from these bench scale tests and field installations suggest that asphalt mixes containing sludge ash can readily be prepared and should perform in an acceptable manner, there is no widespread commercial use of this material in the United States at this time.

The former Metropolitan Waste Control Commission (MWCC) of Minneapolis, Minnesota, (presently the Metropolitan Council of Environmental Services) undertook the most extensive investigations on the use of sludge ash in hot mix asphalt production. Table 17-3 lists a number of field demonstrations undertaken in Minnesota. The results of these demonstrations reportedly revealed no visible difference between the pavement sections containing sludge ash and adjacent sections containing conventional materials.(1)

Table 17-3. Listing of Minnesota test pavements.

Date	Location	Sludge Ash Content	Course
1983	Minneapolis/St. Paul Airport (two bypass roads)	2% and 3%	Base Binder Wearing
1989	Bridge Overpass I-94	2%	Wearing
1990	TH-47, City of Ramsey	2%	Leveling Wearing
1990	TH-97, Forest Lake Twp.	2%	Base Binder Wearing

In 1993, the Suffolk County, New York, Department of Public Works constructed test pads containing sludge ash that was introduced into a New York State Department of Transportation surface mix as a sand substitute.(2) The prepared mixes contained a total of 5.5 percent sludge ash by weight, which accounted for a replacement of 15 percent of the sand or fine aggregate fraction of the mix. Testing of the test pad focused on the surficial texture (skid resistance and surface runoff properties of the ash mixes). Control mix test patches (without ash) were also constructed, and test results of the control mix test patches were compared to the sludge amended mixes. The results provided data that indicated that the presence of ash had no significant effect on the skid resistance of the pavement and was comparable to the control mix.

Previous testing and field demonstration data suggest that sludge ash can be introduced as either a mineral filler or as both a fine aggregate substitute and a mineral filler into an asphalt concrete mix.

MATERIAL PROCESSING REQUIREMENTS

Crushing and Screening

The specification requirements for mineral filler covered in AASHTO M17-83,(3) and listed in Table 17-4, require that 100 percent of the mineral filler must pass the 0.6 mm (No. 30) sieve. To comply with this specification, some sludge ash sources may require crushing and/or screening to remove oversize particles. If used as a combination mineral filler and fine aggregate substitute, no processing will generally be required.

Table 17-4. AASHTO M17-83 specification requirements for Mineral filler for use in bituminous paving mixtures.

Particle Sizing		Organic Impurities	Plasticity Index
Sieve Size	Percent Passing		
0.60 mm (No. 30)	100	Mineral filler must be free from any organic impurities	Mineral filler must have plasticity index not greater than 4
0.30 mm (No. 50)	95 - 100		
0.075 mm (No. 200)	70 - 100		

Vitrification

There are several plants located in Japan that vitrify sewage sludge ash. A recently closed facility operated for several years in Monticello, New York, producing a frit-like aggregate that was suitable for use as a fine aggregate substitute material,(4) and was approved for such use by the New York State Department of Transportation. Vitrification produces a fine aggregate material (not a mineral filler), which permits the introduction of higher percentages of sludge ash into a mix.

ENGINEERING PROPERTIES

Some of the properties of sludge ash that are of particular interest when sludge ash is used in asphalt concrete include particle size, plasticity, and organic content.

Particle Size: Depending on the source of ash, some sludge ash may have a significant fraction of particles greater than 0.6 mm (No. 30 sieve) in size. If this is the case, then sludge ash will not meet the requirements of AASHTO M17 for mineral filler and may have to be processed (crushed and screened) or introduced into the mix as a combination mineral filler and fine aggregate. Sludge ash particles greater than 0.6 mm (No. 30 sieve) in size are expected to comply with gradation and soundness requirements for fine aggregate material outlined in AASHTO M29.(5)

Plasticity: Sludge ash is a nonplastic material and meets the plasticity requirements for mineral filler or fine aggregate outlined in AASHTO M17(3) and AASHTO M29,(5) respectively.

Organic Impurities: Sludge ash can be expected to contain some small percentage (generally less than 2 percent) of organic material, depending on the efficiency of combustion.(6) This small organic fraction does not appear to affect the performance of sludge ash as a mineral filler.

The properties of an asphalt paving mix containing sludge ash that are of particular interest include stability, mix density, air voids, asphalt demand, durability, and asphalt cement viscosity.

Stability: The addition of sludge ash in paving mixes up to approximately 5 to 6 percent by weight of aggregate reportedly increases the stability of the mix.(2,3)

Mix Density: The addition of sludge ash can be expected to decrease the density of the mix.(2,3)

Air Voids and Asphalt Demand: An increase in sludge ash concentration can be expected to result in an increase in air voids and a corresponding increase in the asphalt cement demand of the mix.(2,3)

Durability: Mix durability (measured in the laboratory) may be slightly improved by the addition of sludge ash.(2,3)

Viscosity: The addition of sludge ash to an asphalt cement reduces the ductility of the binder and its penetration values and increases the corresponding viscosity of the binder, producing a high consistency binder.(2)

Although sludge ash can essentially meet the requirements of a mineral filler, as outlined in AASHTO M17, it is likely that when introduced into a paving mix, some of the larger sludge ash particles act as a mineral aggregate material (filling the interstices between coarser aggregate materials). At the same time the silt-sized particles act as an asphalt modifier, forming a high-consistency asphalt grade binder. A high-consistency asphalt grade binder exhibits relatively high viscosity and hardness and low ductility, which could increase the susceptibility of the pavement to thermal cracking.

DESIGN CONSIDERATIONS

Mix Design

Asphalt mixes containing sludge ash can be designed using standard laboratory procedures.

It is recommended that sludge ash in paving mixes be limited to less than 5 percent by weight of aggregate (3 percent for wearing courses). Higher percentages of sludge ash appear to result in excessively high stabilities.(2)

Structural Design

Conventional AASHTO pavement structural design methods are appropriate for asphalt pavements incorporating sludge ash as a mineral filler or fine aggregate.

CONSTRUCTION PROCEDURES

Material Handling and Storage

Sludge ash is a porous, lightweight material that must be introduced into a mineral filler storage silo pneumatically. Due to its lightweight nature, additional silo storage capacity may be required. Wet sludge ash that has been quenched as part of the sludge incineration process cannot be managed in this manner.

Mixing, Placing and Compacting

Sludge ash may be introduced into paving mixes by means of its own hopper or through a mineral filler silo. The same methods and equipment used for mixing, placing, and compacting conventional pavements are applicable to asphalt pavements containing sewage sludge ash.

Quality Control

A quality control program should be adopted when sludge ash is being used in order to monitor the quality (particularly the size distribution) of the source material. The same field testing procedures used for conventional hot mix asphalt mixes should be used for mixes containing sewage sludge ash. Mixes should be sampled in accordance with AASHTO T168,(7) and tested for specific gravity in accordance with ASTM D2726(8) and in-place density in accordance with ASTM D2950.(9)

UNRESOLVED ISSUES

There has been some concern expressed regarding the presence of trace metals in sludge ash. Recent studies in Minnesota(10,11) indicate that leaching does not appear to be a problem, which would seem apparent due to the small percentages of sludge ash actually incorporated into a mix (less than 5 percent). Nonetheless, environmental criteria are needed to establish acceptable sludge ash trace metal content criteria. Additional data are also needed to define specifications regarding acceptable loss on ignition or organic impurity data.

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ORIGIN

Steel slag, a by-product of steel making, is produced during the separation of the molten steel from impurities in steel-making furnaces. The slag occurs as a molten liquid melt and is a complex solution of silicates and oxides that solidifies upon cooling.

Virtually all steel is now made in integrated steel plants using a version of the basic oxygen process or in specialty steel plants (mini-mills) using an electric arc furnace process. The open hearth furnace process is no longer used.

In the basic oxygen process, hot liquid blast furnace metal, scrap, and fluxes, which consist of lime (CaO) and dolomitic lime (CaO•MgO or "dolime"), are charged to a converter (furnace). A lance is lowered into the converter and high-pressure oxygen is injected. The oxygen combines with and removes the impurities in the charge. These impurities consist of carbon as gaseous carbon monoxide, and silicon, manganese, phosphorus and some iron as liquid oxides, which combine with lime and dolime to form the steel slag. At the end of the refining operation, the liquid steel is tapped (poured) into a ladle while the steel slag is retained in the vessel and subsequently tapped into a separate slag pot.

There are many grades of steel that can be produced, and the properties of the steel slag can change significantly with each grade. Grades of steel can be classified as high, medium, and low, depending on the carbon content of the steel. High-grade steels have high carbon content. To reduce the amount of carbon in the steel, greater oxygen levels are required in the steel-making process. This also requires the addition of increased levels of lime and dolime (flux) for the removal of impurities from the steel and increased slag formation.

There are several different types of steel slag produced during the steel-making process. These different types are referred to as furnace or tap slag, raker slag, synthetic or ladle slags, and pit or cleanout slag. Figure 18-1 presents a diagram of the general flow and production of different slags in a modern steel plant.

The steel slag produced during the primary stage of steel production is referred to as furnace slag or tap slag. This is the major source of steel slag aggregate. After being tapped from the furnace, the molten steel is transferred in a ladle for further refining to remove additional impurities still contained within the steel. This operation is called ladle refining because it is completed within the transfer ladle. During ladle refining, additional steel slags are generated by again adding fluxes to the ladle to melt. These slags are combined with any carryover of furnace slag and assist in absorbing deoxidation products (inclusions), heat insulation, and protection of ladle refractories. The steel slags produced at this stage of steel making are generally referred to as raker and ladle slags.

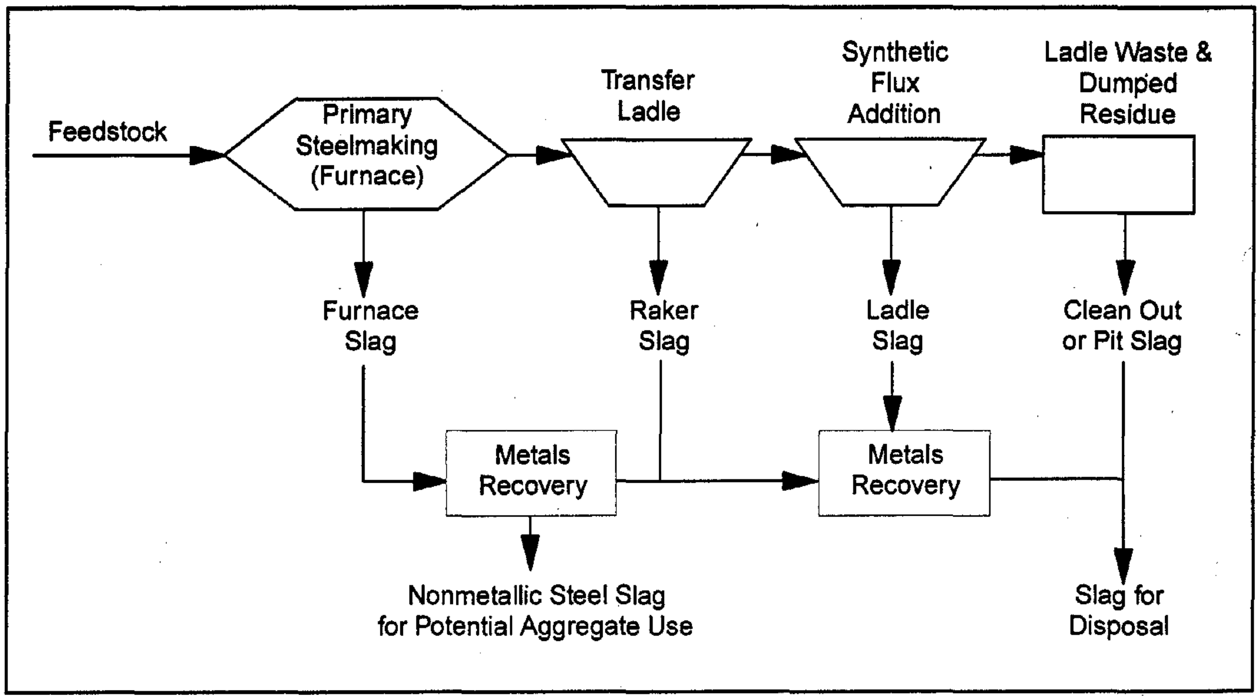

Figure 18-1. Overview of slag production in modern integrated steel plant.

Pit slag and clean out slag are other types of slag commonly found in steel-making operations. They usually consist of the steel slag that falls on the floor of the plant at various stages of operation, or slag that is removed from the ladle after tapping.

Because the ladle refining stage usually involves comparatively high flux additions, the properties of these synthetic slags are quite different from those of the furnace slag and are generally unsuitable for processing as steel slag aggregates. These different slags must be segregated from furnace slag to avoid contamination of the slag aggregate produced.(1)

In addition to slag recovery, the liquid furnace slag and ladle slags are generally processed to recover the ferrous metals. This metals recovery operation (using magnetic separator on conveyor and/or crane electromagnet) is important to the steelmaker as the metals can then be reused within the steel plant as blast furnace feed material for the production of iron.

Additional information on steel slag use in the United States can be obtained from:

National Slag Association
808 North Fairfax Street
Alexandria, Virginia 22314

CURRENT MANAGEMENT OPTIONS

Recycling

It is estimated that between 7.0 and 7.5 million metric tons (7.7 to 8.3 million tons) of steel slag is used each year in the United States.(2) The primary applications for steel slag in the United States are its use as a granular base or as an aggregate material in construction applications.

Disposal

While most of the furnace slag is recycled for use as an aggregate, excess steel slag from other operations (raker, ladle, clean out, or pit slag) is usually sent to landfills for disposal.

MARKET SOURCES

Steel slag can normally be obtained from slag processors who collect the slag from steel-making facilities. Slag processors may handle a variety of materials such as steel slag, ladle slag, pit slag, and used refractory material to recover steel metallics. These materials must be source separated, and well-defined handling practices must be in place to avoid contamination of the steel slag. The slag processor must also be aware of the general aggregate requirements of the end user.

The processing of steel slags for metals recovery is not only important to remove excess steel at the market source for reuse at the steel plant, but is also important to facilitate the use of the nonmetallic steel slag as construction aggregate. This nonmetallic slag material can either be crushed and screened for aggregate use (steel slag aggregates), or sintered and recycled as flux material in the iron and steel furnaces.

Steel slag aggregates generally exhibit a propensity to expand because they contain free lime and magnesium oxides that have not reacted with the silicate structures and that can hydrate and expand in humid environments. This potentially expansive nature (volume changes of up to 10 percent or more attributable to the hydration of calcium and magnesium oxides) could cause difficulties with products containing steel slag, and is one reason why steel slag aggregates are not suitable for use in Portland cement concrete or as compacted fill beneath concrete slabs.

Steel slag destined for use as an aggregate should be stockpiled outdoors for several months to expose the material to moisture from natural precipitation and/or application of water by spraying. The purpose of such storage (aging) is to allow potentially destructive hydration and its associated expansion to take place prior to use of the material in aggregate applications. There is a wide variation in the amount of time required for adequate exposure to the elements. Up to 18 months may be needed to hydrate the expansive oxides.

HIGHWAY USES AND PROCESSING REQUIREMENTS

Asphalt Concrete Aggregate, Granular Base, and Embankment or Fill

The use of steel slag as an aggregate is considered a standard practice in many jurisdictions, with applications that include its use in granular base, embankments, engineered fill, highway shoulders, and hot mix asphalt pavement.

Prior to its use as a construction aggregate material, steel slag must be crushed and screened to meet the specified gradation requirements for the particular application. The slag processor may also be required to satisfy moisture content criteria (e.g., limit the amount of moisture in the steel slag aggregate prior to shipment to a hot mix asphalt plant) and to adopt material handling (processing and stockpiling) practices similar to those used in the conventional aggregates industry to avoid potential segregation. In addition, as previously noted, expansion due to hydration reactions should be addressed prior to use.

MATERIAL PROPERTIES

Physical Properties

Steel slag aggregates are highly angular in shape and have rough surface texture. They have high bulk specific gravity and moderate water absorption (less than 3 percent). Table 18-1 lists some typical physical properties of steel slag.

Table 18-1. Typical physical properties of steel slag.(3)

Property	Value
Specific Gravity	3.2 - 3.6
Unit Weight, kg/m^3 (lb/ft^3)	1600 - 1920 (100 - 120)
Adsorption	up to 3%

Chemical Properties

The chemical composition of slag is usually expressed in terms of simple oxides calculated from elemental analysis determined by x-ray fluorescence. Table 18-2 lists the range of compounds present in steel slag from a typical base oxygen furnace. Virtually all steel slags fall within these chemical ranges but not all steel slags are suitable as aggregates. Of more importance is the mineralogical form of the slag, which is highly dependent on the rate of slag cooling in the steel-making process.

Table 18-2. Typical steel slag chemical composition. (4)

Constituent	Composition (%)
CaO	40 - 52
SiO_2	10 - 19
FeO	10 - 40 (70 - 80% FeO, 20 - 30% Fe_2O_3)
MnO	5 - 8
MgO	5 - 10
Al_2O_3	1 - 3
P_2O_5	0.5 - 1
S	< 0.1
Metallic Fe	0.5 - 10

The cooling rate of steel slag is sufficiently low so that crystalline compounds are generally formed. The predominant compounds are dicalcium silicate, tricalcium silicate, dicalcium ferrite, merwinite, calcium aluminate, calcium-magnesium iron oxide, and some free lime and free magnesia (periclase). The relative proportions of these compounds depend on the steel-making practice and the steel slag cooling rate.

Free calcium and magnesium oxides are not completely consumed in the steel slag, and there is general agreement in the technical literature that the hydration of unslaked lime and magnesia in contact with moisture is largely responsible for the expansive nature of most steel slags.(1,2) The free lime hydrates rapidly and can cause large volume changes over a relatively short period of time (weeks), while magnesia hydrates much more slowly and contributes to long-term expansion that may take years to develop.

Steel slag is mildly alkaline, with a solution pH generally in the range of 8 to 10. However, the pH of leachate from steel slag can exceed 11, a level that can be corrosive to aluminum or galvanized steel pipes placed in direct contact with the slag.

Tufa-like precipitates, resulting from the exposure of steel slag aggregates to both water and the atmosphere, have been reported in the literature.(5) Tufa is a white, powdery precipitate that consists primarily of calcium carbonate ($CaCO_3$). It occurs in nature and is usually found in water bodies. The tufa precipitates associated with steel slags are attributed to the leachate combining with atmospheric carbon dioxide. The free lime in steel slags can combine with water to produce calcium hydroxide ($Ca(OH)_2$) solution. Upon exposure to atmospheric carbon dioxide, calcite ($CaCO_3$) is precipitated in the form of surficial tufa and powdery sediment in surface water. Tufa precipitates have been reported to clog drainage paths in pavement systems.(5)

Mechanical Properties

Processed steel slag has favorable mechanical properties for aggregate use, including good abrasion resistance, good soundness characteristics, and high bearing strength. Table 18-3 lists some typical mechanical properties of steel slag.

Table 18-3. Typical mechanical properties of steel slag.(3)

Property	Value
Los Angeles Abrasion (ASTM C131), %	20 - 25
Sodium Sulfate Soundness Loss (ASTM C88), %	<12
Angle of Internal Friction	40° - 50°
Hardness (measured by Moh's scale of mineral hardness)*	6 - 7
California Bearing Ratio (CBR), % top size 19 mm (3/4 inch)**	up to 300

* Hardness of dolomite measured on same scale is 3 to 4.
** Typical CBR value for crushed limestone is 100%.

Thermal Properties

Due to their high heat capacity, steel slag aggregates have been observed to retain heat considerably longer than conventional natural aggregates. The heat retention characteristics of steel slag aggregates can be advantageous in hot mix asphalt repair work in cold weather.

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INTRODUCTION

Steel slag can be processed into a coarse or fine aggregate material for use in dense- and open-graded hot mix asphalt concrete pavements,(1,2,3) and in cold mix or surface treatment applications.(4) Proper processing of steel slag and special quality-control procedures are extremely important in selecting steel slag for use in asphalt paving mixes. Of particular importance is the potential for expansion because of free lime or magnesia in the slag, which could result in pavement cracking if ignored. Steel slag use in paving mixes should be limited to replacement of either the fine or coarse aggregate fraction, but not both, because hot mix asphalt containing 100 percent steel slag is susceptible to high void space and bulking problems due to the angular shape of steel slag aggregate. Mixes with high void space (100 percent steel slag aggregate mixes) are susceptible to over-asphalting during production and subsequent flushing due to in-service traffic compaction.

PERFORMANCE RECORD

Steel slag has been successfully used as aggregate in wearing course hot mix asphalt and in surface treatments in the United States and internationally. Its use requires proper selection, processing, aging, and testing to ensure that it will perform in accordance with intended design specifications.

At least 11 states (Alabama, California, Illinois, Indiana, Kentucky, Louisiana, Michigan, Missouri, Pennsylvania, South Carolina, and West Virginia) have evaluated the use of steel slag as aggregate in asphalt paving, and one state agency (Louisiana) has been involved in steel slag use in surface treatments.(5)

Some of the positive features of steel slag aggregates in hot mix asphalt include good frictional properties and stripping resistance, high stability, and resistance to rutting/plastic deformation. Use of unsuitable or improperly processed slag, however, can result in performance problems.

Extensive map cracking of pavements has been observed by a number of agencies in the United States (Illinois, Indiana, and Minnesota), Canada, Germany, and Japan. The cracking is related to the volumetric instability associated with free lime (CaO) and/or free magnesia (MgO) in the steel slag. Hydration of the free lime or magnesia results in expansion and cracking of the slag particle. When this reaction occurs in a pavement, cracks or popouts can occur. Recent problems reported in Ohio and Illinois relating to deterioration, ravelling, and the coarse texture of hot mix asphalt containing steel slag aggregate have resulted in some restrictions on steel slag use.(6)

MATERIAL PROCESSING REQUIREMENTS

Quality Control

Special quality-control procedures are needed during steel slag production (at the steel-making plant) and during aggregate processing to ensure that steelworks "rubbish" (furnace brick, wood, incompletely fused fragments, lime, rock, etc.) is not included as part of the steel slag aggregate.

Washing

To control volumetric instability resulting from the presence of potentially hydratable free lime and free magnesia, only suitable high-quality furnace slags that do not contain significant quantities of unreacted lime and dolime should be used. Recent recommended options suggest that the coarse and fine steel slag aggregates be washed and contain less than 3 percent by mass of nonslag constituents, and less than 0.1 percent wood content. Further, it is recommended that no detectable soft lime particles or lime-oxide agglomerations be present.(7)

Crushing and Screening

In addition to cleaning, aging, and quality-control requirements, crushing, screening and magnetic separation are required to produce a suitable coarse or fine aggregate product. Consistency of gradation, unit weight, and absorption are important if steel slag aggregates are to be used in hot mix asphalt, and the aggregate processor must ensure that this is achieved.

ENGINEERING PROPERTIES

There is typically a large variation in the physical, chemical, and mineralogical properties of steel slags. This difference is dependent on the steel-making plant, steel-making process, specific furnace, steel slag processing, and storage strategies. For this reason, the use of steel slag aggregate must be considered on a specific steel-making furnace and processing basis, with recognition of the inherent variability of the slag production and the presence of potentially hydratable free lime and free magnesia.

Some of the properties of steel slag that are of particular interest when steel slag is used in asphalt concrete include gradation, specific gravity, durability, moisture content, absorption, frictional properties, and thermal properties.

Gradation: Steel slag aggregates used in hot mix asphalt must meet the same gradation requirements as conventional aggregate, as outlined in AASHTO T27.(8) For surface treatment, steel slag aggregates should satisfy the gradation and physical requirements for ASTM D1139.(9)

Specific Gravity: Due to the relatively high specific gravity (3.2 to 3.6) of steel slag, steel slag aggregate can be expected to yield a higher density product compared with that of conventional mixes. Bulk relative densities are 15 to 25 percent greater than most conventional mixes.

Durability: Steel slag aggregate is very hard and abrasion resistant. Steel slag aggregates display good durability with resistance to weathering and erosion.

Moisture Content: The relatively rough surface texture (deep pores) of steel slag increases the susceptibility of the aggregate to differential drying and potential retention of moisture in the hot mix. Moisture retention coupled with the presence of hydratable oxides could result in volumetric instability. To minimize drying requirements and the potential for hydration reactions, steel slag aggregate moisture content should be limited to 5 percent prior to use in hot mix asphalt. The moisture content of the steel slag aggregate after drying should be no greater than 0.1 percent.

Absorption: Steel slag has somewhat higher absorption than conventional aggregate. This can result in an increased asphalt cement demand. Asphalt cement extractability (in lab tests) can be more difficult than for conventional aggregate.

Frictional Properties: Experience in several countries with steel slag aggregates in hot mix asphalt suggests that very satisfactory frictional resistance can be anticipated. Polished stone values (PSV, high values desirable) and aggregate abrasion values (AAV, low values desirable) support the general finding that steel slag aggregate exhibits superior frictional resistance for highway pavements.(10) The high frictional resistance, as well as the abrasion resistance of steel slag aggregate, is advantageous in applications where high wear resistance is required, such as industrial roads, intersections, and parking areas subjected to heavy traffic.

Thermal Properties: Steel slag aggregates have been reported to retain heat considerably longer than conventional natural aggregates. The heat retention characteristics of steel slag aggregates can be advantageous for hot mix asphalt repair work during cold weather.

Some of the mix properties that are of interest when steel slag is used in asphalt concrete mixes include stability, stripping resistance, and rutting resistance.

Stability: Steel slag aggregate mixes combine very high stabilities (1.5 to 3 times higher than conventional mixes) with good flow properties.

Stripping Resistance: Steel slag mixes typically exhibit excellent resistance to stripping of asphalt cement from the steel slag aggregate particles. Resistance to stripping is most probably enhanced because of the presence of free lime in the slag.

Rutting Resistance: The high stability (1.5 to 3 times higher than conventional mixes) with good flow properties results in a mix that resists rutting after cooling, but is still compactable. Rutting resistance is advantageous for highways, industrial roads, and parking areas subjected to heavy axle loads.

DESIGN CONSIDERATIONS

Mix Design

Asphalt mixes containing steel slag can be designed using standard laboratory procedures. Mixes combining steel slag aggregate and conventional aggregates are usually designed volumetrically because of the significant difference in aggregate bulk relative densities.

The requirements of ASTM D5106(11) and ASTM D4792(12) outline recommended properties of steel slag aggregate for use in hot mix asphalt. Some agencies, such as the Pennsylvania Department of Transportation, have adopted additional specifications setting minimum aging periods for processed steel slag aimed at limiting the risk of expansive cracking of steel slag aggregate in hot mix asphalt. Internationally, Germany and Japan have comprehensive specifications for the processing of steel slag aggregates that, in addition to aging requirements and aggregate expansion testing, also include expansion testing of the hot mix asphalt incorporating steel slag.(13)

Steel slag aggregate use is limited by many jurisdictions to either coarse or fine aggregate (but not both) to mitigate potential bulking problems (poor compactability and high void space). This problem can also be mitigated by blending the coarse or fine steel slag aggregate with conventional natural (more rounded) materials to facilitate the compactability of the hot mix.

A recent comprehensive assessment of steel slag aggregates in hot mix asphalt use was undertaken in Canada. This assessment resulted in the following recommended tests and performance specifications for slag aggregates:(13)

- Petrographic examination should be undertaken of all steel slag aggregate to identify the presence of deleterious components. No lime or lime-oxide agglomerations should be detected.

- The potential for steel slag expansion should be tested in accordance with ASTM D4792 in a 7-day water immersion test. A maximum expansion limit of 1 percent is recommended.

- Steel slag aggregate hot mix asphalt immersion expansion testing on final Marshall hot mix asphalt plugs should be undertaken to ensure stable hot mix asphalt. No cracking or popouts and only slight staining in steel slag hot mix asphalt briquettes after 72 hours of immersion in 60°C water baths should be acceptable.

- Autoclave disruption testing at atmospheric pressure using accelerated 1-hour tests to give quick information on the slag volume expansion potential should be considered, and acceptable limits should be established based on field performance testing.

These specifications were recommended as a supplement to minimum aging requirements for stockpiles of processed steel slag aggregates.

Structural Design

Conventional AASHTO pavement structural design methods are appropriate for asphalt pavements incorporating steel slag in the mix.

CONSTRUCTION PROCEDURES

Material Handling and Storage

The same general methods and equipment used to handle conventional aggregates are applicable for steel slag aggregates.

Stockpiles for the processed (crushed and screened) coarse and fine steel slag aggregates, however, should be maintained in a consistently wet condition before supply to the hot mix plants. The period of aging in wet stockpiles should be established by process-control testing to satisfy deleterious components criteria (autoclave soundness, ASTM D4792(12) expansion testing). The storage period should be a minimum of 3 and perhaps up to 18 months. Until such time as process-control testing (as outlined above) indicates that the steel slag aggregates are suitable for use in hot mix asphalt, it is recommended that additional aging be required.

Mixing, Placing, and Compacting

Steel slag aggregate moisture content and hot mix asphalt moisture content consistency are important to satisfactory mix production. It is recommended that the maximum moisture content of coarse and/or fine steel slag aggregates upon introduction to the hot mix plant not exceed 5 percent. The maximum moisture content of steel slag aggregate hot mix asphalt should not exceed 0.1 percent.

The same methods and equipment used for conventional pavements are applicable to asphalt pavements containing steel slag.

Quality Control

The same field testing procedures used for conventional hot mix asphalt mixes should be used for mixes containing steel slag. Mixes should be sampled in accordance with AASHTO T168,(14) and tested for specific gravity in accordance with ASTM D2726(15) and in-place density in accordance with ASTM D2950.(16) Cold mix/surface treatments using steel slag should satisfy conventional cold mix/surface treatment materials requirements given by ASTM D1139.(9)

UNRESOLVED ISSUES

Several issues pertaining to the use and subsequent recycling of steel slag aggregates in hot mix asphalt still need to be resolved. Although the incidence of map cracking associated with the use of steel slag aggregates is widely acknowledged, there is a need to determine the extent to which this problem undermines the structural integrity of the pavement. Limited investigations suggest that structural performance is not adversely affected; however, more long-term monitoring data are required to verify influence of the cracking on pavement life expectancy.

Since map cracking is recognized as a performance problem, but is not directly addressed by ASTM and AASHTO standard methods, there is a need to establish standard methods to assess the suitability of steel slag aggregates for hot mix asphalt use and for surface treatment. Also, long-term field performance data are required to assess the performance of surface treatments containing steel slag aggregates.

There is a need to assess the recyclability of steel slag in asphalt pavements incorporating reclaimed asphalt pavement and containing steel slag aggregates. There is presently a concern that recycling steel slag aggregate pavements that have previously exhibited volumetric stability (map cracking) problems could result in similar problems in the recycled mix.(17)

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INTRODUCTION

Steel slag can be used as aggregate in granular base applications. It is considered by many specifying agencies to be a conventional aggregate and can normally exceed the aggregate requirements for granular base. The high bearing capacity of steel slag aggregates can be used advantageously on weak subgrades and in heavy traffic applications. Good interlock between steel slag aggregate particles provides good load transfer to weaker subgrades. Because of their similar particle shape and angle of internal friction, blast furnace slag aggregates have at times been blended with steel slag aggregates to improve yield, without substantial reduction in stability.

PERFORMANCE RECORD

Experience in the United States, Belgium, Japan, The Netherlands, and Germany has shown that steel slag, properly selected, processed, aged, and tested, can be used as granular base for roads in above-grade applications. Steel slag aggregates exhibit a number of very favorable mechanical properties for use in granular base, including very high stability and good soundness. However, steel slag is not widely used for granular base applications where lower quality (and less expansive) aggregates will often suffice. Only four state agencies (California, Indiana, Louisiana. and Michigan) are monitoring the use of steel slag aggregate in base course.(1)

Since volumetric instability of steel slag granular base (due to lime and dolime hydration reactions) has resulted in expansive reactions, steel slag aggregate granular base should not be utilized in confined applications, such as backfill behind structures, granular base, subbase confined by curb and gutter, and trenches.

In addition, the formation of tufa-like precipitates (white, powdery precipitates formed by the chemical reaction of atmospheric carbon dioxide and free lime (CaO) in the steel slag) has resulted in deposits that have clogged subdrains and drain outlets.(2,3) The clogging of drainage paths creates water retention and soft pavement conditions. Frost action on the retained water can result in severe pavement distress.

MATERIAL PROCESSING REQUIREMENTS

Quality Control

Special quality-control procedures are needed during steel slag production (at the steel-making plant) and during aggregate processing to ensure that steelworks "rubbish" (furnace brick, wood, incompletely fused fragments, lime, rock, etc.) is not included as part of the steel slag aggregate.

In addition to control problems associated with volume instability and tufa precipitate formation, only suitable high-quality furnace slags that do not contain significant quantities of unreacted lime and dolime should be used. Belgium and The Netherlands limit the free lime content of steel slags used for granular base applications to 4.5 percent and require that the processed material be weathered at least 1 year to limit volume instability.(4)

Studies indicate tufa formation is likely to occur in highway subdrain applications if the original total lime content (CaO) of steel slags exceeds 1 percent.(5,6)

Although weathering is useful to control the volumetric instability of steel slags, it does not appear to prevent the formation of tufa precipitates.

Washing

Recent recommendations suggest that steel slag aggregates should be washed and should contain less than 3 percent by mass of nonslag constituents, less than 0.1 percent wood content, and have no detectable soft lime particles or lime-oxide agglomerations present.(7)

Crushing and Screening

Prior to use as a granular base material, ferrous components of the steel slag are magnetically separated. Steel slag must be crushed and screened to produce a suitable granular aggregate gradation using processing equipment similar to that for conventional aggregates.

ENGINEERING PROPERTIES

Some of the important properties of steel slag that are of particular interest when steel slag is used as an aggregate in granular base include gradation, specific gravity, stability, durability, corrosivity, volumetric instability, drainage, and tufa formation.

Gradation: Steel slag can readily be processed to satisfy the AASHTO M 147(8) gradation requirements for granular aggregates.

Specific Gravity: Due to the relatively high specific gravity (3.2-3.6) of steel slag, steel slag aggregate can be expected to yield a higher density product compared with conventional mixes (2.5-2.7).

Stability: Steel slag aggregates have high angle of internal friction (40° to 45°) that contribute to high stability and California Bearing Ratio (CBR) values up to 300 percent.

Durability: Steel slag aggregates display good durability with resistance to weathering and erosion.

Corrosivity: The pH value of the steel slag aggregate generally ranges from approximately 8 to 10; however, leachate from steel slag can exceed a pH value of 11. This can be corrosive to galvanized or aluminum pipes placed in direct contact with the slag.

Drainage Characteristics: Steel slag aggregates are free draining and are not susceptible to frost.

Volumetric Instability: Steel slag has a potentially expansive nature. Volume changes of up to 10 percent or more can occur during the hydration of calcium and magnesium oxides.

Tufa Formation: Drainage from steel slag aggregates can result in the formation of tufa-like precipitates, which are powdery deposits that consist primarily of calcium carbonate ($CaCO_3$). Such deposits have clogged drainage paths in pavement systems.(4)

DESIGN CONSIDERATIONS

Properly processed steel slag aggregates can readily satisfy gradation requirements and the physical requirements of AASHTO M147(8) and ASTM D2940.(9) It is recommended that steel slag be tested for expansion potential in accordance with ASTM D4792.(10)

Granular base containing steel slag should be designed so that it is well drained (no standing water) and adequately separated from watercourses to prevent immersion. Pavement joints should be sealed to minimize the ingress of surface water into the steel slag granular base. These provisions are recommended to minimize the potential for leaching of free lime or dolime that may be present in these aggregates, causing tufa deposits.

Conventional AASHTO pavement structural design procedures can be employed for granular base containing steel slag aggregates.

CONSTRUCTION PROCEDURES

Material Handling and Storage

The same general methods and equipment used to handle conventional aggregates are applicable for steel slag.

Stockpiles of processed steel slag aggregate, however, should be maintained in a wet condition prior to delivery to the job site. The period of aging in wet stockpiles should be established by process-control testing to satisfy deleterious components (petrographic examination and ASTM D4792 expansion testing) criteria. Until process-control testing indicates that the steel slag aggregates are suitable for use in granular base, it is recommended that additional aging and reprocessing be required.

Placing and Compacting

The same methods and equipment used to place and compact conventional aggregate can be used to place and compact steel slag. Care is required to avoid placing the material below grade and in locations where it is likely to be immersed in water (to avoid volumetric instability and tufa formation). A good groundwater drainage system is recommended when steel slag aggregate is used to allow free drainage and to prevent ponding within or against the steel slag.

Quality Control

The same field test procedures used for conventional aggregate are recommended for granular base applications when using steel slag. Standard laboratory and field test methods for compacted density are given by AASHTO T191,(11) T205,(12) T238,(13) and T239.(14)

UNRESOLVED ISSUES

There is a need to establish standard methods to assess the suitability of steel slag aggregate for granular base applications and to develop guidelines for the use of steel slag aggregates in this application. Improved testing methods are needed to establish the potential for tufa precipitate formation.

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ORIGIN

Fluorogypsum and phosphogypsum are sulfate-rich by-products generated during the production of hydrofluoric and phosphoric acid, respectively.

Fluorogypsum

Fluorogypsum is generated during the production of hydrofluoric acid from fluorspar (a mineral composed of calcium fluoride) and sulfuric acid. Fluorogypsum is discharged in slurry form and gradually solidifies into a dry residue after the liquid has been allowed to evaporate in holding ponds. When removed from the holding ponds (if it is to be used), the dried material must be crushed and screened. This produces a sulfate-rich, well-graded sandy silt material with some gravel-size particles. Approximately 90,000 metric tons (100,000 tons) of fluorogypsum are generated annually in the United States, mostly in Delaware, New Jersey, Louisiana, and Texas.

Phosphogypsum

Phosphogypsum is a solid by-product of phosphoric acid production. The most frequently used process for the production of phosphoric acid is the "wet process," in which finely ground phosphate rock is dissolved in phosphoric acid to form a monocalcium phosphate slurry. Sulfuric acid is added to the slurry to produce phosphoric acid (H_3PO_4) and a phosphogypsum (hydrated calcium sulfate) by-product.

Phosphogypsum is generated as a filter cake in the wet process and is typically pumped in slurry form to large holding ponds, where the phosphogypsum particles are allowed to settle. The resulting product is a moist gray, powdery material that is predominantly silt-sized and has little or no plasticity.

Approximately 32 million metric tons (35 million tons) of phosphogypsum are produced annually, mostly in central Florida, but also in Louisiana and southeastern Texas. Total accumulations of phosphogypsum are well in excess of 720 million metric tons (800 million tons) and are expected to approach 900 million metric tons (1 billion tons) by the year 2000.(1) As a general rule, 4 to 5 metric tons (4.5 to 5.5 tons) of phosphogypsum are generated for every ton of phosphoric acid produced.

CURRENT MANAGEMENT OPTIONS

Fluorogypsum

Recycling

Fluorogypsum is not being used in any commercial applications; however, fluorogypsum has been evaluated for use as a road base material.(2) It has also been proposed for use in the production of impure plasterboard.(3)

Disposal

All fluorogypsum is currently landfilled or disposed of in holding ponds.

Phosphogypsum

Recycling

Phosphogypsum is a calcium sulfate hydrate that is pumped into ponds, eventually dewatered, and ultimately disposed of in large stockpiles called stacks. Phosphogypsum has been recovered and reused with some success in stabilized road bases,(4) unbound road bases,(5) and roller-compacted concrete.(6) Phosphogypsum can be used for agricultural purposes, if the radium-226 concentration of the source material is less than 10 pCi/g.(7) At the present time, a petition to the EPA is required if phosphogypsum is planned for use in highway applications.(7)

Disposal

At the present time all phosphogypsum is stockpiled in large stacks, some of which may occupy several hundred hectares of land.

MARKET SOURCES

Fluorogypsum

Fluorogypsum may be obtained by contacting the chemical companies that produce hydrofluoric acid in a number of industrialized states, including Delaware, New Jersey, Louisiana, and Texas.(8)

Fluorogypsum that has solidified in sedimentation ponds is removed by blasting, crushing, and screening, much like rock is obtained from a quarry. The recovery and processing of solidified fluorogypsum results in a coarse or "crusher run" type of aggregate with a 38 mm (1-1/2 in) top size and fine calcium sulfate or "natural fines," which is predominantly a sand- and silt-sized material.(2) The recovery and processing of solidified fluorogypsum may be accomplished by commercial aggregate producers who are under contract to the chemical companies.

Phosphogypsum

Phosphogypsum may be obtained by directly contacting phosphate producers located mainly in Florida, Louisiana, or Texas, since the companies that mine phosphate rock and produce fertilizers from it also have ownership rights to the phosphogypsum stacks.

There are, however, environmental concerns regarding radon emanation from phosphogypsum stacks. Special petition requirements, which are defined by the EPA for any commercial use or research activity, must be followed before phosphogypsum can be used.(7)

HIGHWAY USES AND PROCESSING REQUIREMENTS

Fluorogypsum

Embankment, Fill, and Road Base Material

Limited local use has thus far been made of reclaimed dried fluorogypsum. This material has been previously used in West Virginia as a fill material, as a subbase material, and as aggregate in a lime-fly ash stabilized base. The solidified fluorogypsum was blasted, removed, crushed and screened prior to being used as a coarse and fine aggregate material in base course applications.(1)

Phosphogypsum

Stabilized Base Filler

To date, phosphogypsum has been successfully demonstrated as a road base material in stabilized and unbound base course installations and in roller-compacted concrete mixes. The only processing required for the phosphogypsum is the use of a vibrating power screen to break up lumps prior to mixing with a binder.

MATERIAL PROPERTIES

Fluorogypsum

Physical Properties

As previously noted, fluorogypsum solidifies in holding ponds and must be removed, crushed, and graded, if it is to be used as an aggregate substitute material. In the process of size reduction, coarse 38 mm (1-1/2 in) top size material and fine, minus 2.0 mm (No. 10 sieve), sulfate-rich material is produced. The coarse sulfate is a well-graded sand and gravel size material, while the fine sulfate is a silty-clay type material.

Table 19-1 presents some typical fluorogypsum particle size ranges, moisture content and specific gravity values. The average moisture content of the coarse sulfate material reportedly ranges from 6 to 9 percent, while the average moisture content of the fine sulfate material ranges from 6 to 20 percent. The average specific gravity of the coarse and fine sulfate is approximately 2.5, indicating that fluorogypsum is slightly lighter in weight than naturally occurring aggregates, such as crushed limestone or sand and gravel.(1)

Table 19-1. Typical physical properties of fluorogypsum.(9)

Property	Value
Size Range	Coarse Fraction - minus 38 mm (1-1/2 in) Fine Fraction - minus 2 mm (No. 10 sieve)
Moisture Content	Coarse Fraction 6 to 9% Fine Fraction 6 to 20%
Specific Gravity	2.5 (Coarse and fine fractions)

Chemical Composition

Table 19-2 presents an average chemical analysis of samples of coarse and fine fluorogypsum.(1) Fluorogypsum is primarily calcium sulfate with approximately 1 to 3 percent fluoride present. It exhibits slightly acidic properties.

Table 19-2. Typical chemical composition of fluorogypsum (percent by weight).[1]

Constituent	Coarse Sulfate	Fine Sulfate
Sulfate ($CaSO_4$)	71.0	65.6
Fluoride (F)	1.6	2.5
Free Water	8.6	10.4
Combined Water	14.9	15.2
Acidity (H_2SO_4)	.06	.06
pH[a]	4.5	4.6

a. Values of pH expressed in pH units.

Mechanical Properties

Fluorogypsum particles, although solidified in a holding pond, are relatively soft. The results of Los Angeles Abrasion tests performed on a composite sample of coarse fluorogypsum indicate a relatively high abrasion loss of 84 percent.(1)

Phosphogypsum

Physical Properties

As previously noted, phosphogypsum is a damp, powdery, silt or silty-sand material with a maximum size range between approximately 0.5 mm (No. 40 sieve) and 1.0 mm (No. 20 sieve) and between 50 and 75 percent passing a 0.075 mm (No. 200) sieve size. The majority of the particles are finer than .075 mm (No. 200 sieve), and the moisture content usually ranges from 8 to 20 percent. The silty size range of phosphogypsum would classify it as an A-4 soil in the AASHTO soil classification system.(10)

There are two predominant forms of phosphogypsum: dihydrate phosphogypsum ($CaSO_4 \cdot 2H_2O$) and hemihydrate phosphogypsum ($CaSO_4 \cdot \frac{1}{2}H_2O$). Dihydrate phosphogypsum is generally more finely graded than hemihydrate phosphogypsum.

Table 19-3 presents some typical physical properties of phosphogypsum.

Table 19-3. Typical physical properties of phosphogypsum.(5)

Property	Value
Specific Gravity	2.3 - 2.6
Compactive Characteristics: Maximum Dry Density Optimum Moisture	 1470 - 1670 kg/m^3 (92 - 104 lb/ft^3) 15 - 20%

The specific gravity of phosphogypsum ranges from 2.3 to 2.6. The optimum moisture content of either type of phosphogypsum can normally be expected to fall within the range of 15 to 20 percent. The maximum dry density is likely to range from 1470 to 1670 kg/m^3 (92 to 104 lb/ft^3), based on standard Proctor compaction.(5)

These are typical values for phosphogypsum produced in Florida. Values for phosphogypsum produced in other states (such as Texas or Louisiana) may vary somewhat. The addition of fly ash or Portland cement to phosphogypsum yields slightly higher maximum dry density and optimum moisture content values for stabilized phosphogypsum mixtures, in comparison with unstabilized phosphogypsum blends.(11)

Chemical Composition

The major constituent in phosphogypsum is calcium sulfate and, as a result, phosphogypsum exhibits acidic properties. Table 19-4 presents a listing of some typical chemical analyses of phosphogypsum samples from different production areas.(11) Phosphogypsum often contains small residual amounts of phosphoric acid and sulfuric acid and also contains some trace concentrations of uranium and radium, which result in low levels of radiation.

Mechanical Properties

Table 19-5 presents some typical mechanical property values of phosphogypsum. The shear strength of unconsolidated-undrained specimens of unstabilized phosphogypsum has exhibited average internal friction angles of 32 degrees and cohesion values of 125 kN/m^2 (18 lb/in^2). Cement-stabilized specimens have exhibited internal friction angle values ranging from 28 to 47 degrees, and cohesion values from 76 to 179 kN/m^2 (11 to 26 lb/in^2).(12) Coefficient of permeability values for unstabilized phosphogypsum have been found to range from 1.3×10^{-4} cm/sec down to 2.1×10^{-5} cm/sec.

Table 19-4. Typical chemical composition of phosphogypsum (percent by weight).(11)

Constituent	Louisiana	Texas	Florida
CaO	29 - 31	32.5	25 - 31
SO_4	50 - 53	53.1	55 - 58
SiO_2	5 - 10	2.5	3 - 18
Al_2O_3	0.1 - 0.3	0.1	0.1 - 0.3
Fe_2O_3	0.1 - 0.2	0.1	0.2
P_2O_5	0.7 - 1.3	0.65	0.5 - 4.0
F	0.3 - 1.0	1.2	0.2 - 0.8
pH[a]	2.8 - 5.0	2.6 - 5.2	2.5 - 6.0

a. Values of pH expressed in pH units.

Table 19-5. Typical mechanical properties of phosphogypsum.(12)

Property	Value
Friction Angle	32°
Cohesion Values	125 kPa (18 lb/in^2)
Coefficient of Permeability	1.3×10^{-4} to 2.1×10^{-5} cm/sec

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INTRODUCTION

Sulfate wastes, in particular, fluorogypsum and phosphogypsum, can be used in stabilized base and/or subbase applications. These materials are stabilized using either lime and pozzolanic fly ash, Portland cement, or self-cementing fly ash. The stabilized base material is produced, placed, and compacted in essentially the same manner as other lime-fly ash or cement-stabilized base materials. Stabilized base mixtures containing sulfate wastes have strength development and durability characteristics that are comparable to those of conventional stabilized base materials. Any proposed use of phosphogypsum requires special petition to the EPA to demonstrate that the proposed practices will not result in any adverse health or environmental impacts.(1)

PERFORMANCE RECORD

There have been a limited number of stabilized base installations in which either fluorogypsum or phosphogypsum have been used. The most extensive experience to date with each of these materials has been in or around Houston, Texas.

Fluorogypsum

The earliest known application in which fluorogypsum was used in stabilized base compositions occurred during the construction of the TRANSPO '72 International Transportation Exposition held in 1972 at Dulles Airport near Washington, D.C. A portion of the new 40 hectare (100 acre) parking area was used by the Federal Highway Administration (FHWA) to demonstrate the potential for use of base course mixtures containing a number of calcium sulfate wastes including fluorogypsum.

A portion of the parking area was paved with a 127 mm (5 in) thick compacted mixture of 2.5 percent lime, 62 percent fly ash, 18 percent bottom ash, 13 percent crushed limestone, and 2.5 percent fluorogypsum.(2) The overall results from the TRANSPO '72 demonstration project indicated that lime-fly ash-sulfate mixtures were potentially useful for highway base course construction. However, the combination of poor weather and saturated subgrade conditions at the time of construction eventually resulted in the removal and replacement of the experimental base materials.(3)

Fluorogypsum use in stabilized road base has been limited to one demonstration project in West Virginia and several construction projects in Texas. In August 1981, four test sections of lime-fly ash-fluorogypsum, each approximately 3.0 meters (10 feet) wide by 30 meters (100 feet) long, were constructed as side by side pairs within the base course of a plant haul road at the Allied Chemical Company plant in Nitro, West Virginia. Each test section had an increased percentage of fluorogypsum and a decreased percentage of fly ash, while using 5 percent lime. One test section contained 75 percent coarse fluorogypsum sulfate, while the other three contained from 30 to 65 percent fine fluorogypsum.

The 28-day compressive strengths of laboratory test mixes from each of these four test sections ranged from 5090 kPa (738 lb/in^2) to 7625 kPa (1,105 lb/in^2). Retained strengths after freeze-thaw durability testing ranged from 73 to 109 percent of control. All four test sections exhibited satisfactory performance during the first 18 months of exposure and service.(4)

Gulf States Materials, in the Houston area, has produced a number of cement and/or self-cementing fly ash stabilized base materials in which fluorogypsum was used. These compositions have been used in lower volume applications such as parking lots and access roads for businesses and shopping centers, as well as base course layers for residential streets. There are no documented instances of unsatisfactory performance of stabilized fluorogypsum in these applications.(5)

Phosphogypsum

Prior to 1989, when EPA began its regulation of phosphogypsum, a number of stabilized base installations containing phosphogypsum were placed in Florida and Texas. Also, as recently as 1992, the Institute of Recyclable Materials at Louisiana State University had applied to the Louisiana Department of Environmental Quality for a permit to construct a phosphogypsum cement-stabilized road base.(6)

The use of phosphogypsum in stabilized base installations placed in Florida has been limited to only a few experimental pavements involving either phosphogypsum-sand blends sealed with asphalt or roller-compacted concrete mixtures containing Portland cement, sand, and phosphogypsum.(7)

In September 1986, a 2.3 km (1.4 mi) section of roadway in central Polk County was stabilized by placing from 76 mm (3 in) to 152 mm (6 in) of dihydrate phosphogypsum and then mixing the phosphogypsum with the underlying sandy subgrade to a depth of 250 mm (10 in) to 380 mm (15 in) by means of a pulvi-mixer. The base surface was sealed with an RC-70 cutback asphalt, then overlaid with a 25 mm (1 in) layer of asphalt surface.(8)

In late 1986, approximately 2.7 km (1.7 mi) of a section of White Spring Road in northern Columbia County was reconstructed using a blend of one part dihydrate phosphogypsum to two parts subgrade sand by weight as a stabilized base. Approximately 127 mm (5 in) of phosphogypsum was mixed by pulvi-mixer to a depth-approximately 350 mm (14 in) with the sandy soil. The base surface was sealed with an RC-30 cut back asphalt and covered with 25 mm (1 in) to 50 mm (2 in) asphalt concrete surface.(8)

The Polk County roadway was compacted to between 92 and 98 percent of a modified Proctor density. On-site CBR (California Bearing Ratio) measurements taken 1 to 2 months after construction indicated CBR values ranging from 43 to over 100 percent. The Columbia County roadway was compacted to between 92 and 100 percent of the modified Proctor density. The Clegg impact tester was used in lieu of on-site CBR testing for the Columbia County roadway. The Clegg impact values (CIV) ranged from 14 to 38 with an average CIV of 24.3. This CIV corresponds to a CBR value of approximately 40 percent. Minimal distress was observed in these two pavements, indicating the suitability of phosphogypsum as a potential component of stabilized base material.(8)

In February 1988, a demonstration roller-compacted concrete pavement was constructed in the service driveway and parking areas of the Florida Institute for Phosphate Research (FIPR), located in Bartow, Florida. Approximately 1700 m^2 (2,000 yd^2) of pavement were involved. The roller-compacted concrete mix consisted of 13 percent dihydrate phosphogypsum, 14 percent Type II (moderately sulfate resistant) Portland cement, and 73 percent coarse and fine limestone aggregate, proportioned by dry weight. A power screen was used to break up the lumps in the phosphogypsum. The screened phosphogypsum, Portland cement, and limestone aggregates were blended together in a pugmill mixer.(9)

The roller-compacted concrete mix was designed for a compressive strength of 17 MPa (2,500 lb/in^2). Compressive strengths of laboratory Proctor specimens after 74 hours averaged 12 MPa (3,000 lb/in^2). No cracking was observed in the pavement after 3 months in service. Limited observations of performance have led to the conclusion that phosphogypsum-based-roller-compacted concrete is suitable for the construction of parking lot facilities.(9)

From 1983 to 1989, cement-stabilized (or self-cementing fly ash-stabilized) phosphogypsum was frequently used as a roadbase material for city streets, parking lots, truck terminals, shopping centers, and loading platforms in and around the Houston area. The lone supplier of the stabilized base with phosphogypsum (Mobil Chemical Company) has reported greater than a 95 percent success rate on more than 100 projects.(5)

The only unsatisfactory stabilized phosphogypsum projects in Texas resulted from attempts to extend the use of these types of base course installations to state or federally funded roadways. One project using a 10 percent cement-stabilized phosphogypsum base on Texas State Highway 146 proved unsuccessful. Two other projects using varying amounts of self-cementing fly ash and/or Portland cement as stabilization reagents had to be replaced after less than a year in service.(10)

When construction difficulties were encountered, problems were related to either excessive moisture, overstabilization (accompanied by swelling), incomplete mixing, insufficient compaction and sealing, or incompatible stabilizers and prime coats.(5)

MATERIAL PROCESSING REQUIREMENTS

Fluorogypsum

Excavation

Fluorogypsum solidifies in holding ponds and must be excavated and removed, which normally results in both a fine and a coarse fraction. The resultant products are referred to as coarse and fine sulfate.

Crushing or Screening

Besides the initial excavation and breakdown into different size pieces, further processing will usually require some type of crushing and/or screening, much like a conventional aggregate. This can be achieved using standard construction and/or mineral processing equipment.

Phosphogypsum

Drying

Phosphogypsum is a fine, damp, silty material. Construction of stabilized base mixtures in which phosphogypsum is to be dumped and spread, then mixed in place with other additives (sand, cement, and/or self-cementing fly ash) using a pulvi-mixer, essentially requires no processing unless the phosphogypsum is excessively wet. In such cases, the material should be allowed to dry somewhat before being used. If unable to be satisfactorily dried in a stockpile, the wet phosphogypsum may need to be spread out in fairly thin layers for a few days.

Screening

If the phosphogypsum is to be blended with the other additives using a mixing plant, the phosphogypsum should first be passed over a power screen in order to break up any lumps prior to being fed into the plant.

ENGINEERING PROPERTIES

Fluorogypsum

Some of the engineering properties that are of particular interest if fluorogypsum is used as an aggregate in stabilized base and subbase applications include gradation, moisture content, specific gravity, and Los Angeles Abrasion loss.

Gradation: Coarse fluorogypsum typically consists of a combination of gravel and sand size particles, with a top size of 50 mm (2 in), a range of 18 to 50 percent passing the 4.75 mm (No. 4) sieve, and between 10 and 20 percent passing the 0.075 mm (No. 200) sieve. Fine fluorogypsum is a predominantly sand and silt size material with a rather narrow range of gradation, having a top size of 2 mm and from 25 to 50 percent passing a 0.075 mm (No. 200) sieve.(4)

Moisture Content: Coarse fluorogypsum has a moisture content from 6 to 9 percent with an average of 7.5 percent. Fine fluorogypsum has a moisture content that ranges from 6 to 20 percent, with an average of 11 percent.

Specific Gravity: The specific gravity of coarse and fine material is quite uniform and averages 2.50, indicating the fluorogypsum is slightly lighter in unit weight than sand, gravel, or crushed stone.(4)

Los Angeles Abrasion Loss: The Los Angeles abrasion test (ASTM C131)(11) was performed on a composite sample of coarse fluorogypsum. This material corresponded to grading "A" in the test method and had an abrasion loss of 84 percent, which is normally considered high for a base course aggregate. However, the fines generated were nonplastic and potentially reactive, which could enhance the binding of the stabilized matrix (develop higher strength).(4)

Phosphogypsum

Some of the engineering properties of phosphogypsum that are of particular interest in stabilized base and subbase applications include gradation, moisture content, specific gravity, moisture-density relationship, and unconfined compressive strength. It should also be noted that phosphogypsum is usually slightly radioactive and that the level of radioactivity must be determined prior to making any use of the material.

Gradation: The grain size of phosphogypsum typically ranges from approximately 0.50 mm (0.02 in) to 0.02 mm (0.0008 in), with between 60 and 80 percent of all particles being finer than a 0.075 mm (No. 200) sieve. The gradation is generally determined by the degree of grinding received by the ore during the beneficiation process. Phosphogypsum is generally classified as a silt or sandy silt.(12) Material that has been stacked for some time tends to develop agglomerations, thus reducing its fineness or percentage passing the 0.075 mm (No. 200) sieve.

Moisture Content: The moisture content or amount of free moisture in phosphogypsum may range from 3 to 20 percent.

Specific Gravity: The specific gravity of solids ranges from 2.30 to 2.50, with an average in the 2.35 to 2.40 range.(12) Phosphogypsum has little or no plasticity.

Moisture-Density Relationship: Using the modified Proctor compaction method (ASTM D1557),(13) maximum dry density values ranged from 1440 to 1650 kg/m^3 (90 to 103 lb/ft^3) with optimum moisture content values varying from 13 to 18 percent. Maximum dry density values using the standard Proctor compaction method (ASTM D698)(14) were always lower, usually by approximately 5 to 10 percent, with optimum moisture content values for stabilized phosphogypsum blends comparable to unstabilized phosphogypsum.(12)

The addition of Portland cement or fly ash to phosphogypsum yields slightly higher maximum dry density and optimum moisture content values for stabilized phosphogypsum blends, in comparison to unstabilized phosphogypsum.(12)

Unconfined Compressive Strength: The unconfined compressive strength of phosphogypsum when compacted in a standard Proctor(14) mold at an optimum moisture content of 16.7 percent is typically 96 kPa (14 lb/in^2) when soaked and about 1690 kPa (245 lb/in^2) when air dried.(7) These are values for compacted phosphogypsum without the addition of a stabilization reagent.

DESIGN CONSIDERATIONS

Mix Design

Fluorogypsum

The fluorogypsum materials used in the experimental road base sections in West Virginia consisted of a coarse and a fine-graded sulfate aggregate. These materials were blended with varying percentages of lime and pozzolanic fly ash to produce four trial mixes. In each mix, 5 percent lime was used. Fly ash percentages ranged from 20 to 65 percent. One mix contained coarse calcium sulfate at 75 percent. The three other mixes contained fine calcium sulfate at 30 to 65 percent.(4)

The maximum dry density and optimum moisture content conditions for each of these mixes were initially established using standard Proctor (ASTM D698)(14) test procedures. The moisture content identified as optimum is the recommended moisture content for molding test specimens for unconfined compressive strength testing. Testing for unconfined compressive strength and durability should be done in accordance with ASTM C593(15) procedures.

Instead of curing for 7 days at accelerated (38°C (100°F)) temperatures, test specimens may be cured for 7 days at ambient (23°C (73°F)) temperatures. Additional test specimens should also be prepared and cured for 28, 56, and 90 days at ambient temperatures. In blends containing fluorogypsum in mixes outlined above, the unconfined compressive strength criteria of 2760 kPa (400 lb/in^2) may not be achieved after 7 days of curing, but should be exceeded after 28 days of curing.(4)

Phosphogypsum

The parameter that usually governs mix design proportions for stabilized base compositions containing phosphogypsum is the unconfined compressive strength. Unless local or state specifications require otherwise, the criteria for mix proportioning is typically based on the compressive strength and freeze-thaw durability requirements of ASTM C593.(15) This specification, which was originally developed for lime-fly ash-aggregate base course mixtures, requires that stabilized base mixtures attain 2760 kPa (400 lb/in^2) unconfined compressive strength after 7 days of curing at 38°C (100°F) and also after vacuum saturation. The fly ash normally used in such mixtures is pozzolanic fly ash.

The optimum moisture content for cement-stabilized base mixes containing phosphogypsum can be determined in accordance with the test procedures of ASTM D558.(16) Some states (such as Texas) have imposed more stringent strength criteria than ASTM C593 where cement-stabilized base mixtures are designed to achieve a minimum compressive strength of 4500 kPa (650 lb/in^2) after 7 days of curing at 23°C (73°F). Other states (such as Louisiana) specify that soil-cement mixtures have a minimum compressive strength of only 1725 kPa (250 lb/in^2) after 7 days of ambient temperature curing.

Depending on weather conditions, it may be advisable to evaluate durability (wet-dry) testing in accordance with ASTM D559.(17) Since phosphogypsum is only produced in Florida, Louisiana, and Texas, it is unlikely that freeze-thaw durability criteria in these locations will be of significance in determining mix design proportions.

It is recommended that stabilized base mixes containing phosphogypsum be designed as close as possible to optimum moisture content and maximum dry density conditions, as determined by either the modified(13) or standard(14) Proctor test method. The development of compressive strength is directly related to moisture-density characteristics, with the highest strength development occurring at or near the maximum density.(18)

To properly perform a moisture-density test for phosphogypsum, the raw phosphogypsum should be initially dried at a temperature of 55 °C (131 °F) to a constant weight. When using Portland cement as the stabilization reagent, type II (moderately sulfate resistant) cement should be selected.(18)

Trial mixes of phosphogypsum and reagent should be prepared at optimum moisture content using increasing reagent percentages. Test specimens should be sealed in plastic bags, cured, and then tested for 7 day unconfined compressive strength. Longer term (28, 56, and 90 days) curing and compressive strength testing is also recommended to ensure that the design mix does not lose strength over time.

In preparing trial mixes, grinding of the phosphogypsum lumps insures the homogeneity of the mix.(9) An added caution in designing trial mixes with phosphogypsum is not to add excessive reagent in order to obtain strength because swelling may result. It should also be noted that mixtures containing highly acidic (pH less than 3) phosphogypsum were found to result in significantly lower strengths than mixtures containing less acidic (pH around 5) material.(19)

Structural Design

The structural design of stabilized base or subbase mixtures containing sulfate waste (fluorogypsum or phosphogypsum) can be undertaken using the structural equivalency design method described in the AASHTO Design Guide.(20)

Table 19-6 lists recommended structural layer coefficient values for stabilized base or subbase mixtures. The following structural layer coefficient values are derived from studies of pozzolanic and crushed stone base materials performed at the University of Illinois.(21)

Table 19-6. Recommended structural layer coefficient values for stabilized base mixtures.(21)

Quality	Compressive Strength kPa (lb/in^2) (7 days @ 38°C (100°F))	Recommended Structural Layer Coefficient
High	Greater than 6900 (1,000)	$a_2 = 0.34$
Average	4500 to 6900 (650 to 1,000)	$a_2 = 0.28$
Low	2800 to 4500 (400 to 650)	$a_2 = 0.20$

These coefficient values are based on the use of $a_1 = 0.44$ (used for a bituminous wearing surface) and a value of $a_3 = 0.15$ (used for a crushed stone base). Structural layer coefficient values of 0.30 to 0.35 have been recommended for Portland cement-stabilized bases.(20)

The main factors influencing the selection of the structural layer coefficient for thickness design using the AASHTO method are the compressive strength and modulus of elasticity of the stabilized base material. The value of compressive strength recommended for determination of the structural layer coefficient is the field design compressive strength. The field design compressive strength is simulated by the compressive strength developed in the laboratory after 56 days of moist curing at 23 °C (73 °F).(22) However, other curing conditions may be required by various specifying agencies.

CONSTRUCTION PROCEDURES

Construction procedures for stabilized base and subbase mixtures in which sulfate wastes (fluorogypsum and phosphogypsum) are used are essentially the same as those used for more conventional pozzolanic stabilized bases and subbases.

Material Handling and Storage

Fluorogypsum, once it has been crushed and sized, can be stockpiled much like any conventional aggregate. However, lengthy stockpiling is not recommended because the particles may begin to weather or break down over an extended period of time.

Phosphogypsum must be evaluated for its radiation level prior to use. If suitable for use (i.e., radiation level less than 10 pCi/g), phosphogypsum can be stockpiled in the same way as soil. The material should not be stockpiled for an extended period under rainy conditions or it may become excessively wet.

Mixing, Placing, and Compacting

The blending or mixing of sulfate waste in stabilized base mixtures can be done either in a mixing plant or in place. Plant mixing is recommended because it provides greater control over the quantities of materials batched and also results in the production of a more uniform mixture. Mixing in place does not usually result in as accurate a proportioning of mix components as plant mixing.

To develop the design strength of a stabilized base mixture, the material must be well compacted and must be as close as possible to its optimum moisture content when placed.

Plant-mixed materials should be delivered to the job site as soon as possible after mixing and should be compacted as soon as possible after placement. This is particularly the case with mixtures in which self-cementing fly ash is used as an activator.

Stabilized base materials containing sulfate waste should not be placed in layers that are less than 100 mm (4 in) nor greater than 200 to 225 mm (8 to 9 in) in compacted thickness. These materials should be spread in loose layers that are approximately 50 mm (2 in) greater in thickness prior to compaction than the desired compacted thickness. The top surface of an underlying layer should be scarified prior to placing the next layer. Smooth drum, steel-wheeled static rollers are most frequently used for compaction of base materials containing sulfate waste.

Curing

After placement and compaction, stabilized base materials containing sulfate waste must be properly cured to protect against drying and to assist in the development of in-place strength. An asphalt emulsion seal coat should be applied to the top surface of the stabilized base or subbase material within 24 hours after placement. Placement of asphalt paving over the stabilized base is recommended within 7 days after the base has been installed. Unless an asphalt binder and/or surface course has been placed over the stabilized base material, vehicles should not be permitted to drive over the material until it has achieved an in-place compressive strength of at least 2415 kPa (350 lb/in^2).(22)

Special Considerations

Late-Season Construction

Stabilized base materials containing sulfate waste that are subjected to freezing and thawing conditions must be able to develop a certain level of cementing action and in-place strength prior to the first freeze-thaw cycle in order to withstand the disruptive forces of such cycles. For northern states, many state transportation agencies have established construction cutoff dates for stabilized base materials. These cutoff dates ordinarily range from September 15 to October 15, depending on the state, or the location within a particular state, as well as the ability of the stabilized base mixture to develop a minimum desired compressive strength within a specified time period.(22) These cutoff dates are more applicable to fluorogypsum than phosphogypsum, since phosphogypsum is only produced in Florida, Louisiana, and Texas, where winter weather is usually mild.

Use of Self-Cementing Fly Ash

When self-cementing fly ashes are used as a cementitious material in stabilized base mixtures, compaction should be accomplished as soon as possible after mixing. Otherwise, delays between placement and compaction of such mixtures may be accompanied by a significant decrease in the strength of the compacted stabilized base material.(23)

Crack-Control Techniques

Stabilized base materials containing sulfate waste, especially those in which Portland cement is used as the reagent, may be subject to crack development. The cracks are almost always shrinkage related and are not the result of any structural weakness or defects in the stabilized base material. Unfortunately, shrinkage cracks eventually reflect through the overlying asphalt pavement and must be sealed at the pavement surface to prevent water intrusion and subsequent damage due to freezing and thawing. Cracking is also likely to occur when sulfate wastes are blended or stabilized with lime and pozzolanic fly ash, or with self-cementing fly ash.

One approach to controlling or minimizing reflective cracking associated with shrinkage cracks in pozzolanic stabilized base materials has been to saw cut transverse joints in the asphalt surface that extend into the stabilized base material to a depth of 75 to 100 mm (3 to 4 in). Joint spacings of 9 m (30 ft) have been suggested.(22) For parking lots, the joints should be cut in two directions, perpendicular to each other at approximately the same spacing. The joints should all be sealed using a hot-poured asphaltic joint sealant.

UNRESOLVED ISSUES

Fluorogypsum

Because fluorogypsum is the only sulfate waste that dehydrates to form a solid instead of remaining a slurry or sludge, it has somewhat unique properties or characteristics, especially when crushed and sized into coarse and fine fractions. More information is needed concerning the properties or characteristics of fluorogypsum, along with its long-term field performance in stabilized base applications.

Phosphogypsum

Prior to the use of phosphogypsum, a petition to the EPA must be made in accordance with the provisions outlined in 40 CFR Part 61 of the Code of Federal Regulations.(1) To date, there is no known petition that has been made for the use of phosphogypsum in highway applications under the referenced regulation. The primary issue is the radon content and emissions from products containing phosphogypsum both during and after the useful service life of the product. Additional effort is required to determine what concentration and emission levels would be acceptable, and whether there are suitable applications in which phosphogypsum may be used under the terms of these regulatory provisions.

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ORIGIN

Glass is a product of the supercooling of a melted liquid mixture consisting primarily of sand (silicon dioxide) and soda ash (sodium carbonate) to a rigid condition, in which the supercooled material does not crystallize and retains the organization and internal structure of the melted liquid. When waste glass is crushed to sandlike particle sizes, similar to those of natural sand, it exhibits properties of an aggregate material.

In 1994 approximately 9.2 million metric tons (10.2 million tons) of postconsumer glass was discarded in the municipal solid waste stream in the United States. Approximately 8.1 million metric tons (8.9 million tons) or 80 percent of this waste glass was container glass.(1)

CURRENT MANAGEMENT OPTIONS

Recycling

Over the past decade, there have been widespread efforts to recover postconsumer glass. Bottle bill legislation, which provides for deposits during purchase of containers and deposit bottle returns at retail outlets, has been introduced in some states, but more often glass recovery and recycling have been attempted through the collection of waste glass at recycling centers or Material Recovery Facilities (MRFs).

MRFs are facilities that are designed to sort, store, and market municipal solid waste recyclables that are collected at the curb (source-separated materials). Curbside separation of glass involves homeowner or apartment dweller separation of container glass (or glass commingled with other recyclables such as ferrous and aluminum cans and plastic containers) in preparation for the transport of these materials to the MRF. Some communities that do not have curbside collection offer waste glass drop-off locations for collection. At most MRFs, waste glass is hand-sorted by color (white, amber, and green), and crushed for size reduction (generally to less than 50 mm (2 in) in size). Crushed (color-sorted) glass, which is commonly referred to as cullet, is marketed in most locales as a raw material for use in the manufacture of new glass containers.

Traditionally, glass recycling has involved the collection and sorting of glass by color for use in the manufacture of new glass containers. Recycling postconsumer glass from the municipal solid waste stream for use as a raw material in new glass products is limited, however, by the high cost of collection and processing (hand sorting) of waste glass,(2,3) and specifications that limit impurities (e.g., ceramics, ferrous metal, paper, plastics and mixed-colored cullet) in the glass production process. In addition, during collection and handling of glass, high percentages of glass breakage (30 to 60 percent)(4) limit the quantity of glass that can actually be recovered using hand-sorting practices. Given these limitations, traditional glass recycling rates have been relatively low.

Disposal

The EPA has estimated that in 1994 approximately 9.1 million metric tons (10.1 million tons) or 77 percent of the waste glass generated in the United States was landfilled.(1)

MARKET SOURCES

Figure 20-1 provides a schematic representation of the flow of container glass in the United States along with potential recycling options. In most cases, mixed-colored waste glass can

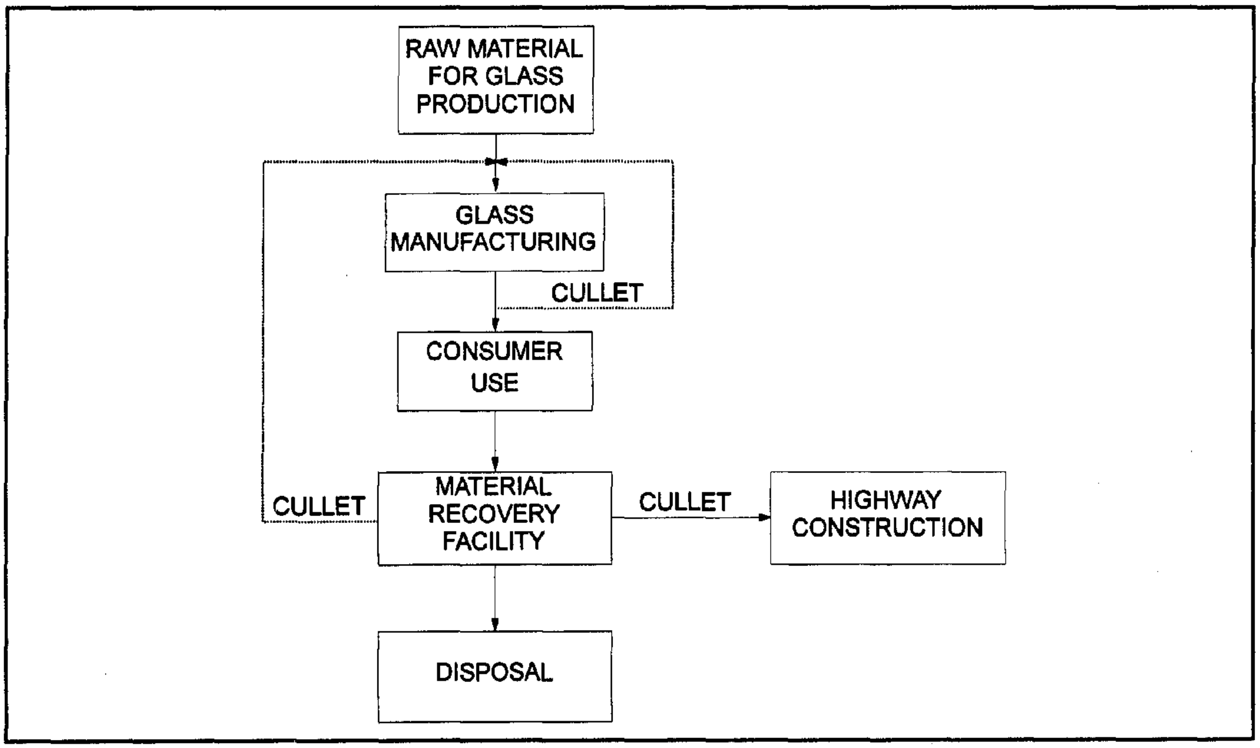

Figure 20-1. General overview of glass cycle in the United States

be obtained by contacting the municipality that is responsible for the collection of recyclables or the MRF operator.

The quality of waste glass obtained from MRFs, which collect and process glass from municipal recycling collection districts, can vary widely and can contain dirt, paper, and plastics. Glass gradation can also vary widely. It can range in top size from 25 mm (1 in) to 100 mm (4 in). The exact physical characteristics of the glass from any given source will depend on the processing equipment (e.g., crushing and screening equipment) at the MRF and the degree of processing afforded the mixed colored glass.

HIGHWAY USES AND PROCESSING REQUIREMENTS

Asphalt Concrete Aggregate

Waste glass has been used in highway construction as an aggregate substitute in asphalt paving. Many communities have recently incorporated glass into their roadway specifications, which could help to encourage greater use of the material.

Granular Base or Fill

Crushed glass or cullet, if properly sized and processed, can exhibit characteristics similar to that of a gravel or sand. As a result, it should also be suitable for use as a road base or fill material.

When used in construction applications, glass must be crushed and screened to produce an appropriate design gradation. Glass crushing equipment normally used to produce a cullet is similar to rock crushing equipment (e.g., hammermills, rotating breaker bars, rotating drum and breaker plate, impact crushers).(4) Because MRF glass crushing equipment has been primarily designed to reduce the size or densify the cullet for transportation purposes and for use as a glass production feedstock material, the crushing equipment used in MRFs is typically smaller and uses less energy than conventional aggregate or rock crushing equipment. Successful production of glass aggregate using recycled asphalt pavement (RAP) processing equipment (crushers and screens) has been reported.(3) Magnetic separation and air classification may also be required to remove any residual ferrous materials or paper still mixed in with the cullet.

Due to the relatively low glass-generation rates from small communities, stockpiles of sufficient size need to be accumulated to provide a consistent supply of material in order for glass use to be practical in pavement construction applications.

MATERIAL PROPERTIES

Physical Properties

Crushed glass (cullet) particles are generally angular in shape and can contain some flat and elongated particles. The degree of angularity and the quantity of flat and elongated particles depend on the degree of processing (i.e., crushing). Smaller particles, resulting from extra crushing, will exhibit somewhat less angularity and reduced quantities of flat and elongated particles. Proper crushing can virtually eliminate sharp edges and the corresponding safety hazards associated with manual handling of the product.

Uncontaminated or clean glass itself exhibits consistent properties; however, the properties of waste glass from MRFs are much more variable due to the presence of nonglass debris present in the waste stream. Table 20-1 lists some typical physical properties of waste glass collected from a number of MRF facilities.(2)

Table 20-1. Selected physical properties of waste glass.

Test	Glass Samples[a]		ASTM Test Method
	Coarse	Fine	
Particle Shape			
Angularity	Angular	Angular	D2488
Flat (%)	20-30	1	
Flat and Elongated (%)	1-2	1	
Specific Gravity[b]	1.96 - 2.41	2.49 - 2.52	ASTM D854[c] ASTM C127[c]
Permeability (cm/sec)	~2 × 10^{-1}	~ 6 × 10^{-2}	ASTM D2434

a. Coarse and Fine glass samples represent minus 19 mm (3/4-in) and minus 6.4 mm (1/4-in) samples, respectively, collected from several MRF facilities unless otherwise indicated.
b. Coarse specific gravity samples represent glass fraction greater than 4.75 mm (No. 4 sieve); fine samples represent glass fraction less than 4.75 mm (No. 4 sieve).
c. ASTM D854 and C127 procedures were used for the coarse and fine fractions, respectively.

Glass collected from MRF facilities can be expected to exhibit a specific gravity of approximately 2.5. The degree of variability in this value depends on the degree of sample contamination and is reflected in the range of specific gravity data shown in Table 20-1.

Crushed glass, which exhibits coefficients of permeability ranging from 10^{-1} to 10^{-2} cm/sec, is a highly permeable material, similar to a coarse sand. The actual coefficient of permeability depends on the gradation of the glass, which, in turn, depends on the degree of processing (crushing and screening) to which the glass is subjected.

The particle size distribution of glass received from MRF facilities can vary greatly. Table 20-2 presents typical glass gradation values for crushed glass received from a New York City MRF.(5)

Table 20-2. Waste glass gradation results.[a]

Standard Sieve Size	Average % Finer
25.4 mm (1 in)	100.0
12.7 mm (1/2 in)	98.7
6.35 mm (1/4 in)	86.0
3.18 mm (1/8 in)	32.6
0.84 mm (No. 20)	6.4
0.42 mm (No. 40)	3.2
0.21 mm (No. 80)	1.5
0.075 mm (No. 200)	0.6

a. Represents waste cullet collected from a City of New York MRF in 1993.

Chemical Properties

Glass-formers are those elements that can be converted into glass when combined with oxygen. Silicon dioxide (SiO_2), used in the form of sand, is by far the most common glass-former. Common glass contains about 70 percent SiO_2. Soda ash (anhydrous sodium carbonate, Na_2CO_3) acts as a fluxing agent in the melt. It lowers the melting point and the viscosity of the formed glass, releases carbon dioxide, and helps stir the melt. Other additives are also introduced into glass to achieve specific properties. For example, either limestone or dolomite are sometimes used in lieu of soda ash. Alumina, lead, and cadmium are used to increase the strength of the glass and increase resistance to chemical attack. Various iron compounds, chromium compounds, carbon, and sulfur are used as coloring agents.

Most glass bottles and window glass are made from soda-lime glass, which accounts for approximately 90 percent of the glass produced in the United States. Lead-alkali-silicate glasses are used in the manufacture of light bulbs, neon signs, and crystal and optical glassware. Borosilicate glasses, which have extraordinary chemical resistance and high temperature softening points are used in the manufacture of cooking and laboratory ware.(6) Table 20-3 lists the typical chemical compositions of these glasses.

Table 20-3. Typical chemical composition of glass types.

Constituent	Soda-Lime(7)	Lead(7)	Borosilicate(8)
SiO_2	70 - 73	60 - 70	60 - 80
Al_2O_3[a.]	1.7 - 2.0	-	1 - 4
Fe_2O_3	0.06 - 0.24	-	-
Cr_2O_3[b.]	0.1	-	-
CaO	9.1 - 9.8	1	-
MgO	1.1 - 1.7	-	-
BaO	0.14 - 0.18	-	-
Na_2O	13.8 - 14.4	7 - 10	45
K_2O	0.55 - 0.68	7	-
PbO	-	15 - 25	-
B_2O_3	-	-	10 - 25

a. Higher levels for amber-colored glass.
b. Only present in green glass.

Glass is generally considered an inert material; however, it is not chemically resistant to hydrofluoric acid and alkalis. Expansive reactions between amorphous silica (glass) and alkalis (such as sodium and potassium found in high concentrations in high alkali Portland cement) could have deleterious effects if glass is used in Portland cement concrete structures.(8,9)

Mechanical Properties

Typical mechanical properties for glass are listed in Table 20-4.(2) Glass is a brittle material that fractures from tensile stress. Gravel-sized glass particles that are greater than 4.75 mm (No. 4 sieve) in size exhibit relatively poor durability when compared with conventional aggregate materials. The internal friction angle or shear strength and the bearing capacity of crushed glass blended with conventional aggregates is relatively high, and its compactibility is relatively insensitive to moisture content. Due to its vitreous, inert nature, crushed glass can be expected to exhibit good soundness properties, but poor frictional properties.

Table 20-4. Typical mechanical properties of waste glass.

Test	Results	Test Method
Los Angeles Abrasion (%)	30 - 42	ASTM C131
Maximum Dry Density, kg/m^e (lb/ft^3) Optimum Moisture (%)	1800 - 1900 (111 - 118) 5.7 - 7.5	ASTM D1557
Angle of Internal Friction (deg)	51 - 53	ASTM D3080
California Bearing Ratio (%) 15% glass 50% glass	 132 42 - 125	ASTM D1883
Hardness (measured by Moh's Scale of Mineral Hardness)	5.5(10)	

Other Properties (Thermal, Reflection, and Glare)

Glass is known for its insulating or heat-retention properties (low thermal conductivity). Aggregates and aggregate mixtures with low thermal conductivity can help to decrease the depth of frost penetration.

Studies conducted at the Colorado School of Mines in the early 1970's reported that glass aggregate pavements take a longer time to cool down due in part to the lower thermal conductivity of glass, when compared to natural aggregates.(11) Recent thermal conductivity test results (ASTM C518) for mixed-colored crushed glass are presented in Table 20-5.(2) Comparison of the results for crushed glass with those for a natural gravelly sand aggregate mix show that glass can be expected to exhibit higher heat retention than natural aggregate materials.

Table 20-5. Thermal conductivity test results.

Material	Apparent Thermal Conductivity[1] Watts/Meter - °K	
	Sample 1	Sample 2
Crushed Glass	0.315	0.260
Gravelly Sand	0.463	0.638

1. Results are presented for two separate samples.

The high reflective properties of glass can be a desirable property in highway construction if they assist in delineating the roadway surface from the surrounding environs. Excessive reflection could, however, result in glare that could adversely affect roadway visibility. There are no documented studies on the quantities of size fractions of glass in pavements that are likely to produce excessive glare. There is, however, a noticeable glass reflection in pavements with glass fractions exceeding 15 percent by weight.

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INTRODUCTION

Waste glass that is crushed and screened can be used as a portion of fine aggregate in asphalt paving mixes. Satisfactory performance has been obtained from hot mix asphalt pavements incorporating 10 to 15 percent crushed glass in wearing surface mixes. The term "glasphalt" has at times been used to describe these pavements. Higher blends, incorporating perhaps up to 25 percent crushed glass, could potentially be used in base or binder course mixes. Hot mix asphalt surface course pavements with more than 15 percent waste glass may experience deterioration due to stripping of the asphalt cement binder from the waste glass.

PERFORMANCE RECORD

At the present time, the commercial use of waste glass in asphalt paving applications has been limited to communities such as the City of New York, where the quantity of waste glass produced and collected provides sufficient incentive to recycle it in pavement applications. Most of the earlier applications of glass use have been limited to test pavements or specialty applications.

In the late 1960's and early 1970's a number of studies and field demonstrations were undertaken in the United States. to examine the potential for using waste glass as an aggregate substitute material in hot mix asphalt. (See references 1,2 3,4,5.) During this period test paving strips were placed at approximately 33 locations throughout the United States and Canada.(6)

From the mid-1970's through the mid-1980's, the City of Baltimore made use of glass in its street pavement program. At least 17 streets were paved with glass to produce a "sparkle" effect, resulting from the reflection of sunlight or street lamp light off the glass pavement. In the mid-1980's research activities were undertaken on Long Island and a glass processing plant was designed and began operations, processing over 12,600 metric tons (14,000 tons) of mixed waste glass for use as an aggregate substitute in paving applications.(7)

More recently, numerous paving projects using waste glass have been undertaken around the country. However, by far the most aggressive program has been undertaken by the City of New York's Department of Transportation, where from 1990 through 1995 approximately 225,000 metric tons (250,000 tons) of glass has been used in resurfacing applications.(8)

Flat and elongated particles that could contribute to pavement raveling, stripping, poor skid resistance, abnormally high tire wear, and excessive glare were all identified by early researchers as potential problems. Since glass does not absorb any of the asphalt cement binder, and since glass is also hydrophilic, moisture damage (stripping) is a particular concern that has been identified, especially when high percentages and large gradations are introduced into a surface course mix.(9) Many of the early investigators recommended the addition of lime as an antistripping agent to reduce potential stripping problems. Early glasphalt projects used high percentages of glass (greater than 25 percent by weight of the mix) with coarse glass gradations (greater than 12.7 mm (1/2 in)). Current data suggest that the use of high glass percentages and large particles of glass probably contributed to most of the stripping and raveling problems that were reported during the early test pavement demonstrations of the 1960's and 1970's.

The high angularity of cullet, compared with rounded sand, can enhance the stability of asphalt mixes where properly sized cullet is used. Stabilities comparable and, in many cases, better than those of conventional mixes have been reported.(5,7,10) Other beneficial characteristics include low absorption and specific gravity and low thermal conductivity, which reportedly offers enhanced heat retention in mixes with glass.(10)

MATERIAL PROCESSING REQUIREMENTS

Cleaning

When used in asphalt concrete, glass must be processed to remove ferrous and nonferrous metal, plastic, and paper. In most waste glass processing plants this requires screening, magnetic and eddy metal current (non-ferrous metal) separation, air classification, and/or handpicking operations. Although 100 percent removal of all paper, plastic, and debris from postconsumer glass streams is unlikely, an acceptable glass product can be achieved in most instances, particularly if mix designs limit glass to 10 to 15 percent of the mix.

Crushing and Screening

Crushing and screening are required to achieve proper sizing and to eliminate flat and/or elongated and sharp-edged glass particles.

ENGINEERING PROPERTIES

Some of the glass properties that are of particular interest when glass is used as fine aggregate in asphalt paving include gradation, specific gravity, and durability.

Gradation: Waste glass used in asphalt surface pavements should be processed to a fine aggregate size (less than 4.75 mm (No. 4 sieve) and blended with conventional aggregates to conform to gradation requirements in accordance with AASHTO T27.(11) Larger top sizes ranging from 9.5 mm to 15.3 mm (3/8 to 5/8 in) should be suitable for use in base course mixes.

Specific Gravity: Due to a specific gravity approximately 10 to 15 percent below conventional aggregates, waste glass can be expected to provide a greater yield (more volume of asphalt concrete per ton).

Durability: Glass is a brittle material and coarse particles greater than 4.75 mm (3/8 in) in size can be expected to break down during handling. Consequently, it is preferable to process (crush and screen) waste glass into a fine aggregate size, which is minus 4.75 mm (No. 4 sieve), prior to its use in surface course asphalt paving mixes.

Some of the properties of an asphalt mix containing glass that are of particular interest include frictional properties, mix stability, stripping resistance, and reflectivity.

Frictional Properties: Skid resistance test results have shown waste glass pavements falling within recommended skid resistance testing limits. Nonetheless, large glass particles (greater than 19 mm (3/4 in) in size) that have at times been incorporated into poorly processed surface course pavements could become slick when wet and should be avoided in all surface mixes containing glass.

Mix Stability: The angular shape and high friction angle (approximately 50°) of well-crushed glass contributes to good lateral stability. This is a positive feature, particularly where vehicular braking and acceleration are considerations.

Stripping Resistance: Glass is not absorptive and bonds poorly to asphalt binder. Antistripping agents such as hydrated lime introduced as 2 percent of the aggregate mix by weight have been used in previous demonstrations to reduce potential stripping problems. Poor immersion-compression test results (retained stability), a measure of the potential for stripping problems, can also be expected where a high percentage of oversized glass particles are introduced into a mix.(10)

Reflectivity: Large percentages of glass in a surface pavement (greater than 15 percent by weight) produce a noticeable increase in the reflectivity of the pavement. Depending on the size of the glass particles, this could produce a noticeable glare, particularly on wet pavements. Smaller glass particles and lower percentages of glass can help to reduce reflective glare problems.

DESIGN CONSIDERATIONS

Mix Design

Asphalt mixes containing crushed glass can be designed using standard laboratory procedures. Conventional fine hot mix aggregate gradations, as specified in AASHTO M29,(12) may be used. It is recommended that mix design testing include stripping potential evaluations as outlined in AASHTO T283.(13)

Currently most highway departments allow the use of 5 to 10 percent glass in their asphalt mixes. Although some areas use 6.4 mm to 12.7 mm (1/4 in to 1/2 in) gradations and larger, many users are taking a more conservative approach to gradation size. The City of New York has lowered its specified gradation top size in its mix design from 15.3 mm (5/8 in) to minus 9.5 mm (3/8 in). Los Angeles has specified the use of minus 9.5 mm (3/8 in) glass. Studies in Virginia and Florida also have recommended that minus 9.5 mm (3/8 in) gradation be used.(9)

Most data at the present time indicate that larger, gravel-sized glass particles will reduce pavement performance, and that optimum performance can best be achieved by using crushed glass as a sand or fine aggregate substitute (less than 4.75 mm (No. 4 sieve)). When waste glass is used as a fine aggregate substitute material, glass performance in hot mix asphalt should be comparable to conventional mixes.(14)

Where larger, gravel-sized glass particles are used, raveling and stripping in particular could be a problem. The introduction of an antistripping agent such as hydrated lime (approximately 2 percent by weight of aggregate) could be beneficial, but performance should be satisfactory if only fine-grained (minus 4.75 mm (No. 4 sieve) glass is used and substitution rates do not exceed 15 percent.

Base course applications, being less susceptible to stripping, rutting and skid resistance, could tolerate the introduction of glass particles up to 15.3 mm (5/8 in) in size, resulting in substitution of both coarse and fine aggregates in the mix. Although higher percentages could probably be introduced, a 15 percent weight limitation would provide for a conservative design. Extraneous debris (e.g., paper, dirt, etc.) sometimes associated with waste glass can be expected to adversely impact mix quality. The introduction of excessive debris from Material Recovery Facilities can be expected to increase the void content of most mixes, if the asphalt content or the mix gradation is not adjusted. Recent recommendations suggest that extraneous debris should be limited to 5 percent of the glass by weight to avoid significant impacts on glass quality.(15)

Structural Design

Conventional AASHTO pavement structural design methods are appropriate for asphalt pavements incorporating waste glass in the mix.

CONSTRUCTION PROCEDURES

Material Handling and Storage

The same methods and equipment used to store or stockpile conventional aggregates are applicable for waste glass, particularly where glass is properly precrushed to a fine, sand-size fraction (where additional breakdown is not a concern).

Mixing, Placing, and Compacting

The same methods and equipment used for conventional pavements are applicable to asphalt pavements containing waste glass.

Quality Control

The same field testing procedures used for conventional hot mix asphalt mixes should be used for mixes containing waste glass. Mixes should be sampled in accordance with AASHTO T168,(16) and tested for specific gravity in accordance with ASTM D2726(17) and in-place density in accordance with ASTM D2950.(18)

UNRESOLVED ISSUES

The development of uniform specifications concerning sizing, levels of debris and mix limitations are needed to facilitate glass use. There is some uncertainty regarding the need for antistripping agents such as lime if glass is reduced to a very fine aggregate size (less than 6.35 mm (1/4 in)). The most limiting constraint to glass use is the lack of an adequate and consistent supply of the product. In only a few instances, such as in the City of New York, have provisions been made to establish a continuous market supply of glass. The elimination of hand sorting and crushing of all glass to produce a market-ready aggregate product is probably required to achieve more widespread glass use.

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INTRODUCTION

Waste glass that has been crushed and screened has the potential for use as a granular base material. Glass that has been reduced to a fine aggregate size fraction (less than 4.75 mm (No. 4 sieve) in size) exhibits properties similar to that of a fine aggregate or sandy material, with relative high stability, due to the angular nature of crushed glass particles. Blending with other coarse conventional materials will typically be required to meet required granular base gradation specifications.

PERFORMANCE RECORD

No documented demonstrations or commercial applications of waste glass in granular base applications have been identified. Nonetheless, recent evaluations of glass aggregate properties suggest that properly processed waste glass blended with appropriately sized aggregates is well suited for use as a granular base material.(1)

MATERIAL PROCESSING REQUIREMENTS

Crushing and Screening

Waste glass should be crushed and screened prior to use to produce a material that will be free of sharp edges and glass slivers, and that will meet the requirements of a fine aggregate material as defined by AASHTO M29.(2)

Cleaning

Waste glass should be free of ferrous and nonferrous metal, and the level of inorganic and organic debris should be reduced as much as practical. It has been recommended that levels of debris in the waste glass should be limited to 5 percent as determined by the American Geophysical Institute (AGI) test method.(3) The AGI test method is a visual test in which small samples are placed on a grid and extraneous debris counted and measured by weight.

ENGINEERING PROPERTIES

Some of the properties of waste glass that are of particular interest when glass is used in granular base applications include gradation, density, friction angle, bearing capacity, durability, and drainage characteristics.

Gradation: Crushed glass collected from Material Recovery Facilities can be expected to exhibit a relatively wide variation in top sizes. Differences in gradation are dependent, in great part, on the type of glass crushing equipment used. In general, however, crushed glass can be expected to be a well-graded material, and properly sized cullet or cullet-aggregate mixtures can yield engineering properties that compare very well with natural aggregates used in granular base applications. Waste glass should be crushed and screened to produce a material that satisfied the grading requirements of granular base specifications, such as AASHTO M147.(4)

Unit Weight and Compacted Density: Crushed glass has a unit weight of approximately 1120 kg/m^3 (70 lb/ft^3), which is lower than that of conventional aggregate. The compacted density of crushed glass will vary with the size and grading of the glass as well as the degree of contamination (extraneous debris, such as paper, plastic caps, and soil). A maximum dry density of approximately 1800 to 1900 kg/m^3 (111 to 118 lb/ft^3) has been reported, which is also somewhat lower than that of conventional granular material. Crushed glass exhibits a relatively flat moisture-density curve, which indicates that the compacted density is insensitive to moisture content.

Stability: Relatively high angles of internal friction (compared with conventional aggregates) of greater than 50° have been reported for crushed glass with top sizes of 19 mm (3/4 in) and 6.4 mm (1/4 in). California Bearing Ratio (CBR) test results of crushed glass blended with conventional aggregate were found to exhibit values ranging from 42 to 125 percent for blends of 50 percent glass with crushed rock. Lower glass additions of 15 percent were found to exhibit values almost identical to that of the crushed rock used in the tests (approximately 133 percent).(1)

Durability: Larger size glass particles have marginal durability, as measured by the Los Angeles Abrasion test, with values of approximately 40 to 45 percent. This suggests that additional processing (crushing) of the waste glass would be desirable to eliminate the larger, less durable glass fraction.

Drainage: Crushed glass is a free-draining material that exhibits permeabilities ranging from 10^{-1} to 10^{-2} cm/sec, depending on the glass gradation.

DESIGN CONSIDERATIONS

Mix Design

Crushed waste glass (cullet) used in granular base applications should be limited to the replacement of fine aggregate sizes. Fine crushed glass contains durable sand-like particles and exhibits consistent properties. Recommended gradations are presented in Table 20-6. Crushed glass in this size range will perform as a highly stable (angular) fine aggregate material. It has been recommended that maximum cullet content should be limited to 15 percent in granular base applications and 30 percent in subbase applications.(1)

Table 20-6. Recommended cullet gradation for use as a structural fill or granular base material.(1)

Size	% Finer
6.35 mm (1/4 in)	10 - 100
1.68 mm (No. 10)	0 - 50
0.42 mm (No. 40)	0 - 25
0.075 mm (No. 200)	0 - 5

Maximum dry density of cullet-aggregate mixes should be determined by the Modified Proctor Test (ASTM D1557). Debris levels should be limited to 5 percent as determined by the American Geophysical Institute visual method(3) to ensure the use of a clean material.

Structural Design

Conventional AASHTO pavement structural design procedures can be employed for granular base containing waste glass.

CONSTRUCTION PROCEDURES

Storage and Material Handling

The same general methods and equipment used to handle conventional aggregates are applicable for waste glass. When combined with natural aggregates, crushed glass should be uniformly mixed.

Placing and Compacting

The same methods and equipment used to place and compact conventional aggregate can be used to place and compact waste glass.

Quality Control

The same field test procedures used for conventional aggregate are recommended for granular base applications when using waste glass. Standard laboratory and field test methods for compacted density are given by AASHTO T191,(5) T205,(6) T238,(7) and T239.(8)

UNRESOLVED ISSUES

Monitored field demonstration programs should be undertaken to better document the performance of granular glass bases in actual applications. Field density test methods, using the nuclear gage density test, require verification.

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INTRODUCTION

Any proposal to incorporate a nonconventional material, and particularly a waste or by-product material, into a pavement structure requires, in addition to an engineering evaluation, an evaluation of environmental, occupational safety and health, recyclability, economic and implementability issues. All of these issues need to be addressed prior to determining the acceptability of the material. Such an evaluation is complicated by the number of technical disciplines as well as institutional considerations that must be included in the process.

There is, in general, an absence of documented procedures, including evaluation tests, assessment procedures, and criteria to address many of the aforementioned issues. The purpose of this chapter is to outline a recommended procedural framework whereby one can decide if a waste or by-product material can be used as a substitute for a conventional material.

The framework presented is intended for use by a waste or by-product material generator who is interested in finding markets for his or her material, the transportation or environmental official who must evaluate the proposal and assess the suitability of the material and the application, or perhaps a legislative body that may be considering mandated use of a material in a specific pavement construction application.

THE EVALUATION FRAMEWORK

There are six major steps in a nonconventional material evaluation process that should be considered:

1. Identify all relevant engineering, environmental, occupational health and safety, recyclability, and economic issues associated with the proposed material and application.

2. Establish laboratory testing and assessment procedures and criteria that the material and the product should meet prior to its acceptance.

3. Test and assess the results of the material and application for approval or disapproval using the established procedures and criteria defined in Step 2.

4. Consider (if the material does not meet the established criteria) the possibility of modifying the material or the product prior to rejecting the material.

5. Identify issues that could impose significant constraints on the implementability of the proposal.

6. Determine whether a field demonstration is necessary to supplement evaluation and assessment tests and criteria and implement the demonstration, if required.

Figure 21-1 depicts a general schematic of the steps involved in this framework. Such a framework is not meant to be rigid in its order, since many of the individual steps could be combined or undertaken in different chronological sequence.

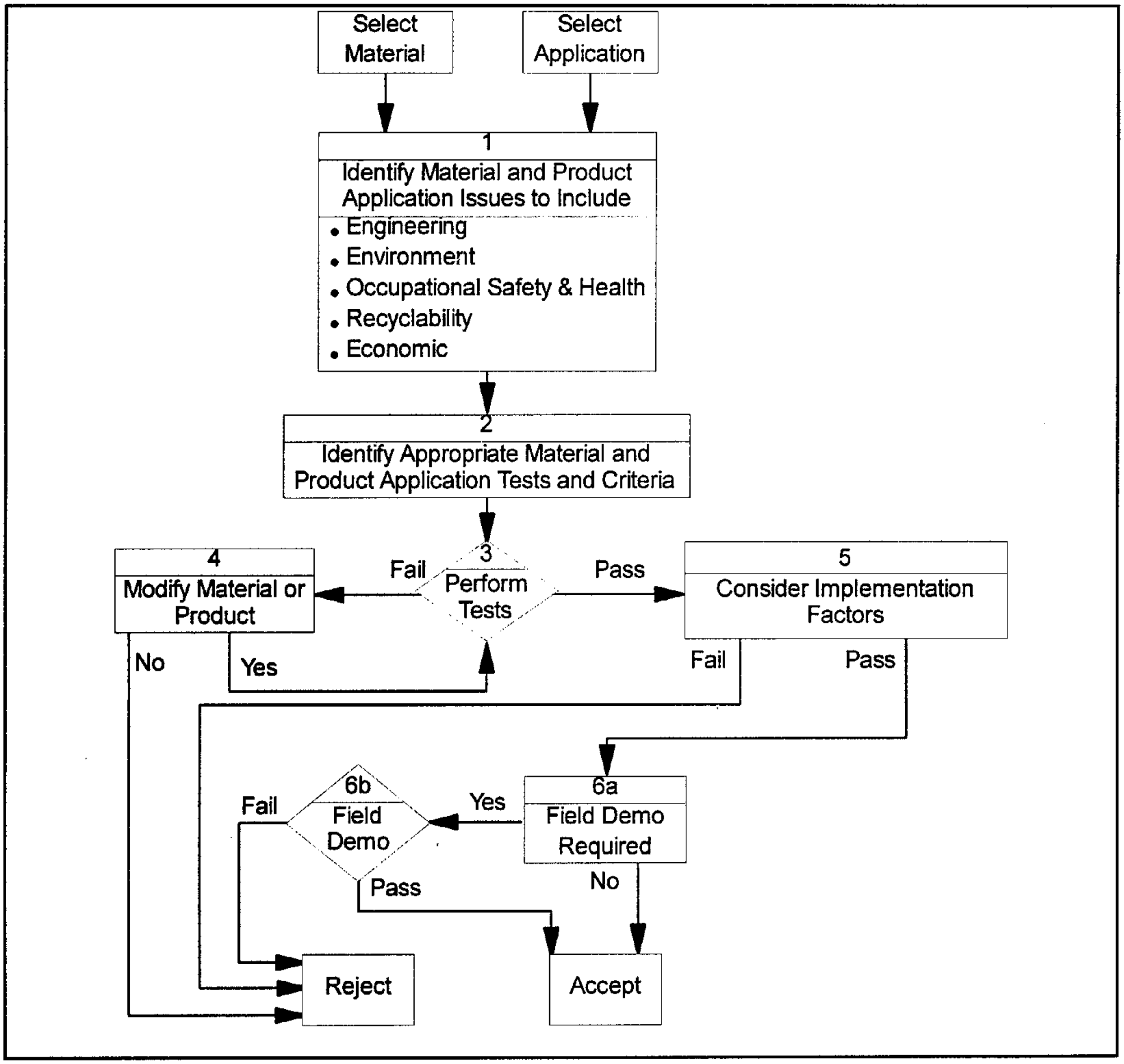


Figure 21-1. Non-conventional material pavement application evaluation framework.

STEP 1 - IDENTIFY RELEVANT ISSUES

Engineering, environmental, occupational health and safety, recyclability and economic issues can normally be identified by assembling a technical review team capable of identifying the specific requirements associated with using a material in a proposed application.

During this planning stage, emphasis should be placed on compiling and assessing existing data, which can include previous laboratory testing, field demonstrations, and the performance history from previous projects (including projects in other states) that have made use of the proposed material in the proposed application. Incorporating existing data into this process can be of great assistance in defining all relevant technical issues and avoiding any unnecessary duplication of prior efforts.

Some recommended engineering questions that should be considered are as follows:

- What is the purpose of the material in the proposed application?
- What are the physical or chemical properties associated with the proposed material that could have an impact on the quality of the product?
- Can these properties be measured and evaluated using conventional material test methods and criteria?

Some recommended environmental questions that should be considered are as follows:

- Is the material a nonhazardous waste as defined by regulatory requirements (e.g., RCRA)?
- What are the chemical constituents or physical characteristics associated with the product that could be of environmental concern?
- What are the operations that the materials might be subjected to during processing, production, construction, and service life that could result in environmental impairment?

Some recommended occupational safety and health questions that should be considered are as follows:

- What material properties (physical or chemical) associated with the material or product might be of concern?
- Is there a Material Safety Data Sheet (MSDS) form for the material?

- How might workers be adversely exposed to the material or its product during its production, placement, and service life?

Some recommended recyclability questions that should be considered are as follows:

- What are postservice life recycling applications that can be expected for the product?
- What are the material properties (physical or chemical) that could adversely affect the environment in postservice life applications?
- What are the material properties (physical or chemical) that could adversely affect the engineering properties of materials or products that may be produced using the waste or by-product material after its initial service life?
- What are the material properties (physical and chemical) that could adversely affect the health and safety of workers testing and handling the material and/or product?

Some recommended economic questions that should be considered are as follows:

- What is the avoided disposal cost of the material?
- What are the additional design and construction costs, if any, associated with the proposed application?
- What are the additional (or reduced) maintenance costs, if any?
- How will the service life of the product be impacted?
- Will the avoided disposal cost offset all other costs?

STEP 2 - ESTABLISH TESTS AND CRITERIA

Once the technical issues that require resolution have been defined in Step 1, then tests and criteria can be established to resolve these issues. At the present time, however, there is an absence of generally accepted test methods and criteria to address all of the engineering, environmental, occupational safety and health, and recyclability issues that in general will arise when assessing the use of nonconventional materials in pavement applications.

Despite this absence of standardized evaluation tests and procedures, nonconventional materials have been used and have performed in an acceptable manner. Materials that have been used with the greatest success have generally undergone significant laboratory and field demonstration testing to ensure that performance criteria defined for the material and application could be met. In some cases (e.g., blast furnace slag, recycled asphalt pavement, and coal fly ash) special American Society of Testing Materials (ASTM) test methods and specifications have been developed and criteria for use have been established.

For many of the nonconventional materials being proposed for use (or those that might be proposed in the future), tests and criteria must be established for each technical issue.

Engineering

The test methods and criteria that are typically used to verify the engineering suitability of conventional materials have been formalized in ASTM and AASHTO specifications. These specifications, which generally include test methods and criteria, address broad categories of material and products that are typically used in pavement construction, including aggregates and fillers, cementitious materials used in asphalt and Portland cement concrete, as well as materials used in embankment and fill and stabilized base (soil-cement) applications.

ASTM and AASHTO test methods and criteria, however, have been established primarily for the evaluation of conventional materials, and are based, in great part, on empirical correlations between the measured material test properties of these conventional materials and recorded field performance that have evolved over several decades.

When a nonconventional material (and particularly a waste or by-product material) is proposed for use in a pavement application, unless the proposed material exhibits characteristics that are identical (or at least very similar) to those of conventional materials, the applicability of the ASTM or AASHTO test methods and criteria may be questionable, and test modifications or new test methods may be needed.

As part of the engineering evaluation process, it is recommended that the following engineering testing issues be considered:

- Establish a list of standard tests that can be used to evaluate the material, and select acceptable criteria.
- Identify modified test procedures or performance testing methods that may be applicable and target criteria to assist in developing design requirements.
- Consider the need to supplement laboratory testing with subsequent field evaluations.

Environmental

Chapter 22 of this report presents a more detailed description of the environmental evaluation issues (including public health) and assessment methods that are available to evaluate waste and by-product material pavement application proposals. In general, the following environmental evaluation issues should be considered:

- Define assessment criteria to establish maximum acceptable contaminant level in the material and the product.
- Define criteria to establish maximum acceptable release of physical and chemical constituents (emissions or leaching) from the material and the product.
- Define laboratory test and evaluation methods that can be used to quantify maximum contaminant levels and potential releases.

Occupational Safety and Health

The potential for exposure to dust, fumes, sharp edges, corrosive liquids, etc., are all issues that need to be considered when evaluating a waste or by-product material. To properly assess occupational safety and health issues, it is recommended that the following occupational safety and health testing issues be considered:

- Establish laboratory or field tests that may be needed to better characterize dusting, gaseous fumes, material properties (e.g., sharp edges), and corrosive liquids that could result from the incorporation of the material into the proposed applications.
- Define criteria that would be considered acceptable relative to worker health and safety concerns.

Recyclability

When new materials are introduced into pavements, there is a need to consider the potential recyclability of the material or product at the end of its functional service life. The original material or product, at that time, can become a new raw material or perhaps a component of a new product.

From an engineering point of view, assessing potential recyclability requires that the designer satisfy himself or herself that there are no significant engineering property considerations that might preclude future use or recycling of the material or product containing a waste or by-product material. Similarly, from an environmental or occupational safety and health viewpoint, it is necessary to ensure that recycling of the pavement will not result in any adverse impact to the environment.

It is recommended that the following recyclability testing issues be considered:

- Establish laboratory, field tests, or assessment procedures if needed, that can be used to determine whether recycling the material will result in adverse engineering impacts.
- Establish laboratory, field tests, or assessment procedures that can be used to determine whether recycling will result in adverse environmental impacts.
- Establish laboratory, field tests, or assessment procedures that can be used to determine whether recycling will result in adverse occupational health and safety impacts.

STEP 3 - PERFORM TESTS

The third step in the evaluation process is the implementation of testing and assessment procedures to determine whether the material will meet the criteria established.

STEP 4 - MODIFY MATERIAL OR PRODUCT

If a material is not capable of meeting established material or product criteria, it is useful to consider whether additional or alternative material processing or product modification could achieve the desired results.

For example, if a waste or by-product material contains a larger fraction of fine-grained particles than desirable for use as a substitute aggregate (i.e., the material is unable to meet the target specifications), screening or blending with coarse material could be used to modify the composite product gradation in order to comply with the required specifications. Alternatively, a modified product design (e.g., mix design) might be able to compensate for the fineness of the material.

STEP 5 - IMPLEMENTATION FACTORS

Even if it is possible to satisfy all of the engineering, environmental, occupational safety and health, recyclability, and economic issues associated with the use of a nonconventional material in a pavement application, there are still some intangible, nontechnical issues that could prevent widespread implementation. These nontechnical issues are lumped under the category of implementation factors. The implementation factors include institutional acceptability, political acceptability, and public acceptability.

Institutional Acceptability

Institutional acceptability is a factor that accounts for all the steps that will be required to gain acceptance of the material. This includes the initial testing and demonstration of the applications, the development of specifications for material use, and the degree to which engineers will be willing to accept and specify the material (if not mandated).

Depending on the particular material and its proposed use, the length of time required in such a process and the degree to which the material will be accepted should be considered in a decision to move forward with the proposed application. For example, a proposal to use a potentially reactive material as an aggregate in Portland cement concrete will, in most instances, require long-term field testing to establish the suitability of the applications and might ultimately result in a reluctance to use the material if the demonstration data are not conclusive. A material with marginal environmental properties could require a comprehensive health risk assessment process, which may require an investment of time and money that may not be commensurate with the benefits associated with recycling the material, and may still leave many engineers reluctant to use the material at the end of the process .

Political Acceptability

Political acceptability includes the expected level of support from public officials for the proposed use. This support may be directly related to the perceived benefits to the public if the proposed material use strategy is implemented. For example, one could be expected to receive greater political support for a proposal to use scrap tires (a highly visible waste material) in pavement construction applications than quarry by-products. Such political support can be expected to translate into institutional benefits, particularly as it relates to the timeline for demonstration and the development of specifications.

Public Acceptability

Public acceptability is a factor that must be considered in any process. Adverse public reaction to a proposed material-application strategy can be expected in many instances to ultimately erode political and institutional support. Sometimes it may be prudent to select an application that will be viewed more favorably by the public, even if a technically equal or more suitable other application exists. For example, the use of a waste or by-product material in a traffic lane wearing surface may be technically feasible, but it may be advisable to propose its use in a base course to provide a protective layer over the by-product modified pavement, or to use it in roadway shoulders rather than in traffic lanes to reduce any concerns that may be anticipated by the public.

STEP 6 - FIELD DEMONSTRATION

The sixth step in the recommended process is the field demonstration.

Demonstrations are normally undertaken to resolve technical issues (engineering, environmental, occupational safety and health, and recyclability) that cannot be fully addressed in a laboratory environment. They may also be undertaken to address implementation factors by providing field data to reassure the public that the proposed application will not result in adverse roadway safety or environmental problems, even if the laboratory data suggest that such is the case..

Proper planning is critical for the implementation of a successful demonstration to ensure that all monitoring equipment, construction, and quality control procedures are in place.

FINAL DECISION

The ability to arrive at a final decision regarding the acceptability of a material for use will depend on the degree to which each of the aforementioned steps were planned and implemented. The establishment of a stepwise framework with specific objectives, procedure and criteria is critical to implementing an evaluation approach that will address all necessary issues.

INTRODUCTION

The Resource Conservation and Recovery Act of 1976 (RCRA) and its subsequent amendments and regulations provide an environmental regulatory framework for the testing, reporting, storage, treatment, and disposal of waste materials in the United States. There is, however, no analogous regulatory framework for selecting, characterizing, recovering, and recycling of waste and by-product materials.

The absence of such a regulatory framework is, in most cases, an obstacle to recycling, since the prospective recycler is uncertain what target environmental criteria must be achieved in terms of material or product quality. At the same time, the absence of such formal regulatory testing, reporting, and management safeguards can result in the use of waste and by-product materials in applications that may be environmentally unsuitable.

Given the lack of formal procedures and criteria for recovery and use of waste or by-product materials, the following general guidance should be followed by all prospective recyclers of waste and by-product materials in pavement construction applications:

> All wastes or by-product materials that are being considered for use, regardless of whether or not the material is exempt from regulation under RCRA, should be evaluated prior to use to fully assess the inherent hazard potential of the material, if used in the proposed application. Simply because a waste ***legally*** may not be subject to hazardous waste regulation is not necessarily an indicator that it is not potentially ***chemically*** hazardous or contains constituents that could pose threats to human health or the environment, nor is it necessarily an indicator of whether it may still be subject to other state or federal environmental laws. For example, RCRA allows for enforcement actions in cases where a ***solid*** (nonhazardous) waste may present an imminent or substantial endangerment to health or the environment. Under the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA or "Superfund"), the release of hazardous substances from a RCRA-exempt or nonhazardous waste in a manner that poses a threat to human health or the environment can also lead to enforcement actions.

The remainder of this chapter is intended to provide the prospective user with general guidance pertaining to federal and state laws, regulations, and regulatory and evaluation requirements that he or she may face when proposing to use waste and by-product materials in pavement construction applications. It includes a description of:

- Previous Federal legislative and regulatory activities and their influence on current waste and by-product material use regulations that are being adopted by the states.

- Current regulatory practices, including both the general requirements that an applicant may face when proposing the use of a waste or by-product material, and specific procedures for obtaining approval to use a waste or by-product material reported in a survey of state environmental regulatory officials.

- General information needed to perform an assessment of the environmental acceptability of a waste or by-product material in pavement applications.

- Specific environmental issues associated with the materials and operations that are unique to pavement construction applications.

PREVIOUS REGULATORY AND LEGISLATIVE ACTIVITY

Historical Perspective

Prior to 1970, there was little if any environmental regulatory oversight regarding the use of waste and by-product materials in pavement construction applications. In general, those materials that exhibited acceptable engineering properties and were both cost-effective and not considered to be "harmful" to workers or the environment were often used. During that period, however, there were no specific procedures or criteria available to quantify potential environmental concerns or harmful impacts.

Three pieces of Federal legislation that were passed by Congress in a span of approximately 11 years from 1969 to 1980, and the implementing rules and regulations that followed, initiated a series of fundamental changes in the management of waste and by-product materials in this country. They presently affect the way in which regulatory agencies address waste and by-product material use. These acts included:

- The National Environmental Policy Act of 1969 (NEPA).

- The Resource Conservation and Recovery Act of 1976 (RCRA).

- The Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA or "Superfund").

NEPA introduced the requirement that environmental impact statements be prepared on all Federal actions significantly affecting the quality of the environment. This requirement was subsequently adopted by states and local governments to provide regulatory oversight over a broad range of environmentally related activities and also to provide mechanisms for public interface and review of these activities as part of a formal environmental permitting process.

RCRA introduced the concept of the separate management of hazardous and nonhazardous wastes, and defined procedures to identify whether a waste is hazardous or nonhazardous. Two types of hazardous wastes were identified. They are referred to as listed wastes or characteristic wastes. A listed waste is a waste that is classified as hazardous due to its source and the way it is produced. These types of wastes are "listed" by EPA in its regulations. A characteristic waste is a waste that must be tested to determine if it exhibits one of four properties: (1) ignitability, (2) corrosivity, (3) reactivity, or (4) toxicity. A waste exhibits the characteristic of toxicity (sometimes called the toxic characteristic or TC rule) if the concentration of any of 39 selected analytes in the Toxicity Characteristic Leaching Procedure (TCLP) extract (formerly the Extraction Procedure Toxicity Test (EP rule), which required the analysis of 14 analytes) exceed regulatory action levels. A hazardous or nonhazardous characterization of waste and by-product materials used in pavement-related applications will almost always be dependent on the results of the TC rule.

CERCLA was designed to address the release or imminent release of hazardous substances into the environment and established the mechanisms for responding to those releases and assessing liability. Regulations and procedures that evolved from CERCLA introduced the concept of human health risk assessments. The development of human exposure reference levels was accelerated as part of these assessment procedures. These reference levels represent the human intake dose below which adverse health effects are not expected to occur. CERCLA also provided the legal framework for assigning liability and assessing monetary damages for environmental impairment.

Although none of the three laws or their implementing regulations directly addressed the use of waste and by-product materials in pavement-related construction applications, they provided the framework that was and is presently used by state environmental regulatory agencies as part of their evolving regulatory strategies.

Evolving Regulatory Strategies

In general, from the mid-1970's (the post-RCRA era) and on into the mid-1980's, RCRA provided the primary means for judging the acceptability of using or not using a waste or by-product material. If a material was found to be nonhazardous (almost exclusively by the EP or TC rule), then the material was considered suitable for use.

Since a hazardous waste designation under RCRA requires special manifest, storage and disposal procedures to ensure public health and safety, it is reasonable to expect that only nonhazardous materials or materials that are excluded from RCRA would be candidate materials for use in pavement construction applications. It is also reasonable to expect, however, that since the RCRA framework is based on the assumption that the waste or by-product material, if it is nonhazardous, will be managed by landfilling or incineration, introducing a waste or by-product material into the environment in recycling applications would require a revised (and perhaps more stringent) regulatory or evaluation framework by which to judge the suitability of such a strategy.

As a result, commencing in the mid-1980's, regulatory agencies began to incorporate additional environmental requirements, including preparation of environmental assessments (based on NEPA) and, in some cases, human health risk assessments (based on CERCLA) to evaluate potential impacts associated with waste and by-product use in construction applications. These evaluations have been used as the basis for determining whether permits should be issued for material use.

The adoption of these more rigorous and comprehensive evaluation procedures was also catalyzed by CERCLA-related liability concerns and public involvement in the assessment and permitting process.

Recent Assessment Activities

Most of the initial environmental assessments, which were prepared during the late 1980's, were sponsored by the Electric Power Research Institute (EPRI) and local power companies and were designed to obtain field data and/or assess the suitability of using coal combustion residues (i.e., coal fly ash, bottom ash, boiler slag, and flue gas desulfurization sludges) in highway construction applications. (See references 1, 2, 3, 4, 5, 6, and 7.)

More recently, applications for use of municipal waste combustor ash have resulted in the preparation of a number of environmental and human health risk assessments. (See references 8, 9, 10, and 11.)

In November 1994, the EPA issued a risk and environmental assessment(12) that was used as the basis for supporting EPA's rulemaking activity covering the use of high temperature metal recovery (HTMR) slags in pavement applications (i.e., as an antiskid or deicing material, as an aggregate substitute in asphalt pavements, as a road base/subbase material and as an additive in the manufacture of cement). HTMR slags are residues produced from high temperature metal recovery treatment of electric arc furnace dust.

CURRENT REGULATORY PRACTICES

General Requirements

Due primarily to the increased pressure to recover and use waste and by-product materials, in recent years, most state environmental regulatory agencies (especially those in industrial areas) have begun the process of formalizing their regulatory procedure for approving the use of waste and by-product materials. In many states this is referred to as a Beneficial Use Permit Process or Beneficial Use Determination (BUD). At the present time, however, there are no universally accepted environmental approval and permitting procedures.

Regulatory requirements in general can take one or more of the following forms:

1. No approval is required — material is considered acceptable due to previous history of use (grandfather clause).

2. RCRA approval is required — material must not exhibit the characteristics of a hazardous waste.

3. Environmental or risk assessment is required — a field and/or desktop evaluation must be provided to demonstrate that the material will have no adverse impact on human health and the environment.

Although the first two requirements are rather straightforward, the latter requirement can necessitate a series of evaluations that could include the preparation of an environmental assessment, a human health risk assessment, or an ecosystem risk assessment.

There are notable distinctions between the more traditional environmental assessment and human health risk assessments or ecosystem risk assessments; however, beneficial use regulations in general have not clearly delineated these differences or indicated when one or more of these assessments may be required as part of a permitting process.

Environmental assessments generally require a quantification of emissions or discharges from a proposed activity (e.g., construction of a pavement using a waste or by-product material) and a projection of the impact of this emission or discharge on the ambient environment. The magnitude of the impact is usually assessed by comparing the source discharge or the projected ambient impact to some source discharge standard (e.g., groundwater or surface water discharge limits) or some ambient air, water or soil quality standard (e.g., ambient air or water quality criteria). Projections of impacts to the ambient environment are normally estimated using environmental models (e.g., air and water quality models).

Human health assessments, which are an outgrowth of CERCLA and which were originally intended to provide a framework for developing the risk information necessary to assist in decision making for remediation at hazardous waste disposal sites, provide for a linking of discharges and emissions from specific sources to vulnerable human receptors in an attempt to quantify risks (using reference doses for carcinogenic and noncarcinogenic effects) associated with a specific activity. They attempt to account for all potential contaminants and exposure routes (e.g., ingestion, inhalation, and dermal absorption) that might affect the identified receptor.

Ecosystem risk assessments are evaluations that focus on potential impacts to flora and fauna, usually in the immediate environment of the action. Like human health risk assessments, they tend to focus on specific transfer routes to identifiable flora and fauna and the impact on these organisms. They sometimes address long-term cumulative impacts that may result from the proposed action, such as bioaccumulation and potential food chain effects.

State Regulatory Approaches

In January 1996, a survey was conducted by the New York State Department of Environmental Conservation on behalf of the Association of State and Territorial Solid Waste Management Officials (ASTSWMO), located in Washington, D.C. A questionnaire was sent to all 50 states to obtain information regarding the environmental regulatory approaches presently used to manage waste and by-product material recycling applications in the United States.

The survey form consisted of questions requesting information pertaining to the existence and nature of any regulatory review or permit process facing a prospective waste or by-product material user or applicant prior to proceeding with the use of the material in a recycling application. It also included a request for a description of the general provisions of the process.(13)

A total of 39 states and the District of Columbia provided sufficiently informative responses to allow characterization of their regulatory processes. Of the 40 respondents, 17, or 42 percent, indicated that they required that the applicant receive a formal permit prior to using waste or by-product materials. Nineteen, or 48 percent, indicated that they had an informal review process with no permit required. Four states, or approximately 10 percent, indicated that they had no process.

Table 22-1 presents a summary of the information received from each of the responding state environmental regulatory agencies. Included in Table 22-1 is a listing of the type of procedures required and specific comments regarding details associated with the review or permit process. A key to Table 22-1 provides clarification to the comments presented in the table.

Although most states report the availability of either a review or permit process, specific evaluation procedures that would be expected of an applicant were unclear in almost all cases. Many states reported that evaluations were done on a case-by-case (CbC) basis or that an environmental assessment (EA) was required. No specific assessment approaches or evaluation criteria were available. Some states required that a market be available, while others simply

Table 22-1. Summary of state regulatory procedures.

Permit Required	Review Process Only	No Requirements
Arizona - NGA	Alaska - CbC	Colorado
California - NH, EA	Arkansas - CbC	Washington, DC
Delaware - Market	Connecticut - CbC	North Dakota
Illinois - NH, Market, EA	Florida - NH, Site	Utah
Kentucky - NGA	Georgia - NH	
Louisiana - NGA	Idaho - NGA	
Maine - NGA (D)	Indiana (D) - NH	
Massachusetts - NH, EA	Iowa - CbC	
Michigan - NH	Kansas - NGA	
Minnesota - NGA	Maryland - NH, Market	
Nebraska - CbC	Missouri - CbC	
New Hampshire - CbC	North Carolina (D) - NH	
New Jersey - NH	Oklahoma - NGA	
New York CbC, Market	South Carolina - CbC	
Ohio - NH	South Dakota - CbC, NH	
Oregon - NGA	Tennessee - CbC	
Pennsylvania - NGA	Texas - NH, Market	
	Vermont - CbC	
	Washington - CbC	

Key:

Review (D):	Review process; formal permit process being developed.
None:	No review or permits required.
Market:	Proof of market required.
NH:	Material must test as nonhazardous according to appropriate state or Federal regulations.
EA:	Requires an environmental assessment to determine that adverse impacts will not occur to the environment, animals, or to human health.
Site:	Requires postinstallation periodic monitoring of the site.
CbC:	Requirements for reuse are determined on a case-by-case basis.
NGA:	No written guidelines available.
NGA (D):	No written guidelines available; process being developed.

required that the material be nonhazardous (NH). One state reported that periodic monitoring of any new application would be required.

The results of the survey suggest that, until such time as more definitive formal criteria are established, in most cases applicants will be required to define the procedures with the appropriate regulatory agency on a case-by-case basis.

GENERAL ASSESSMENT REQUIREMENTS

Although there are few formal procedures or criteria for establishing the environmental suitability of using waste and by-product materials in pavement construction applications, there are common elements to all environmental assessments that form the basis for determining the potential impacts associated with a proposed application. These common elements include the following:

- Identification of potential hazards posed by the use of the material.
- Identification of persons or media (e.g., air, water, soils) likely to be impacted by the identified hazard.
- Identification of the magnitude of the potential impact.

Identification of Potential Hazards

Some waste and by-product materials may contain concentrations of trace metals or trace organics that are higher in concentration and/or more environmentally mobile than those found in conventional materials. Others may contain highly alkaline materials (e.g., free lime), high concentrations of soluble salts, or very fine particles that may be susceptible to dusting and may also be respirable. Still others may contain volatile organic or inorganic material that could be released in high-temperature environments. Table 22-2 lists categories of potential environmental hazards ("parameters") and outlines specific concerns which might be associated with those hazards.

Impacted Persons or Media

The pavement construction process comprises numerous operations including material storage, handling, production, placement, demolition, excavation, and disposal or recycling operations. These operations are all part of the pavement production, construction, service life, and postservice life activities, and the identification of each of these operations is important when identifying impacted persons or media. Potential dust emissions, volatile emissions, or liquid discharges from these operations could have an impact on ambient air, surface water, groundwater, soils, or the worker environment.

Table 22-3 presents a listing of common operations, environmental release mechanisms, and impacted media associated with most pavement-related applications where waste and by-product

Table 22-2. Chemical and physical properties of environmental concern.

Parameters	Potential Hazardous Property
Leachable (or soluble) trace metals	Presence of extractable and mobile metals such as As, Cd, Cu, Cr, Hg, Pb, Zn, etc., that could impact groundwater and surface water quality.
Leachable (or soluble) trace organics	Presence of extractable trace organic compounds such as benzenes, phenols, vinyl chloride, etc., that could impact groundwater and surface water quality.
Leachable corrosivity (highly acidic or alkaline materials)	Presence of extractable and mobile alkalinity or acidity that could impact the pH of groundwater or surface water.
Soluble solids	Presence of soluble and mobile salts that could impact groundwater quality and sensitive freshwater environments.
Total and respirable dust	Presence of fine particulate matter that is respirable or is susceptible to airborne migration.
Trace metals present in total and respirable dust	Presence of trace metals in fine mobile particulate that could be inhaled or deposited at secondary locations.
Trace organics present in total and respirable dust	Presence of trace organics in fine mobile particulates that could be inhaled or deposited at secondary locations.
Volatile metals	Volatile metals such as As, Hg, Cd, Pb, and Zn, which could be released at high temperature (mostly a worker health issue).
Volatile organics	Volatile organics such as chlorinated hydrocarbons which could be released at high temperatures (mostly a worker health issue).

materials may be used. A more detailed examination of these operations, release mechanisms, and transport media is presented in the next section entitled, "Environmental Issues — Pavement Applications."

Table 22-3. Pavement application exposure pathways.

Source Operations	Release Mechanisms[a]	Impacted Media[b]
Stockpiles Screening Crushing Blending Conveying Transport Drying Placement Demolition Recycling	Primary Dispersion of: Fugitive Dust, Particulate Abrasion, and Point Source Particulate Emissions	Dispersion Into the Worker Air Environment and into the Ambient Air Environment
	Secondary Deposition of Air Emissions	Other Media (Land, Water)
Drying	Primary Dispersion of Volatile Emissions	The Worker Air Environment and Ambient Air Environment
	Secondary Condensation and Deposition	Other Media (Land, Water)
Stockpiles Service Life Disposal	Primary Discharges of Surface Runoff Containing Soluble Components or Particulates	Surface Waters and Groundwater
	Secondary Deposition and Absorption	Other Media (Soils, Sediments)
Stockpiles Service Life Disposal	Primary Leaching of Soluble Components	Groundwater and Surface Waters
	Secondary Deposition and Absorption	Other Media (Soils)

(a) Primary mechanisms refer to those transport processes that result in "direct" transport from the source operation to the impact media. Secondary mechanisms refer to additional processes, after the primary process, that result in transport to a second or third media.

(b) The Worker Air Environment represents the airspace of the worker and is subject to OSHA regulations; the Ambient Air Environment is the greater airspace that would be regulated by ambient air quality regulations.

Magnitude of Impact

Techniques for determining the magnitude of the impact will depend in great part on the type of evaluation that is required (i.e., traditional environmental assessment, human health risk assessment, or ecosystem risk assessment). In all cases the use of source emission, ambient air, surface water, and groundwater models will probably be required.

Guidance on the selection of these models and methods for determining the magnitude of potential impacts can be obtained from several sources. The first source to check is the agency requiring the assessment, which may have specific requirements for models and criteria to use in determining the extent of estimated impacts. A second source is previously completed assessments, such as references 1-11, which may contain guidance on previously used and accepted models. Finally, the EPA and EPRI have published several guidance documents that may be useful for determining potential impacts. (See references 14,15,16,17,18,19,20, 21,22,23,24,25,26,27.)

The suggested sources of guidance presented in this section are not intended to be exhaustive, but are intended as guidance and a possible starting point in the impact assessment process. In preparing an assessment it may be determined that adequate information is not available to satisfactorily perform a comprehensive evaluation. In such cases field demonstration programs may be required as part of the assessment process to assist in the development of source emission data.

ENVIRONMENTAL ISSUES — PAVEMENT APPLICATIONS

Material Characteristics

During the preparation of these guidelines, insufficient data were found to be available to adequately define whether most of the waste or by-product materials included in the guidelines pose significant environmental risks if used in pavement applications. Inasmuch as previous practices did not require testing of such materials for their environmental properties, future efforts will be required to obtain this type of data.

Despite the lack of material-specific environmental data, it is possible, based on an examination of pavement materials and their applications, to provide generic insight into potential environmental issues associated with waste and by-product materials that may be used in pavement applications. This can be accomplished by considering the characteristics of the material (e.g., is it a dust susceptible to airborne emission?), how much of the material is actually introduced into the pavement (e.g., relative quantity), and the activities and operations to which the material and pavement will be subjected during its production and processing, construction, service life, and postservice life.

Pavement Applications

The pavement applications covered in these guidelines can be subdivided into five major categories. They include: (1) asphalt concrete applications, (2) Portland cement concrete applications, (3) flowable fill applications, (4) stabilized base applications, and (5) unbound aggregate and fill applications (includes granular base and embankment and fill).

Waste and by-products that are used in these pavement applications are generally used as a replacement for a conventional material or as a modifier or admixture. Within these applications, a given material may have one or more of the following possible uses:

- Aggregate in asphalt or Portland cement concrete
- Mineral filler (asphalt concrete)
- Asphalt cement modifier
- Supplementary cementitious material (Portland cement concrete)
- Flowable fill aggregate
- Flowable fill pozzolan or initiator
- Stabilized base aggregate
- Stabilize base pozzolan or initiator
- Granular base
- Embankment and fill material

A list of these material categories, including the general pavement application, physical properties, purpose and approximate percentage of material used in each of the respective applications, is presented in Table 22-4. From a relative environmental perspective, it is reasonable to expect that the higher the percentage of recycled material that is incorporated into a pavement structure, the greater the potential concern that might arise regarding the use of the material. The magnitude of this concern will ultimately depend on the nature and level of contamination associated with the subject material.

The information presented in Table 22-4 suggests that the major uses of recovered materials in paving can be expected to occur in the aggregate and fill replacement applications. Asphalt modifiers, Portland cement concrete supplementary cementitious materials, and stabilized base and flowable fill pozzolans or initiators make up relatively small percentages of the pavement product (e.g., almost always less than 5 percent). There would only be a small likelihood that these materials could result in significant environmental impacts when used in these relatively low percentages. In addition, while aggregates and fill materials are generally stored, processed, transported, blended, and placed in the open environment, asphalt modifiers, Portland cement and supplementary cementitious materials, and pozzolans and initiators used for flowable fill are generally stored and handled in closed containers until they are applied to the product.

Finally, incorporating waste and by-product materials into asphalt or Portland cement concrete pavements, flowable fill, or stabilized bases, or placing these materials in bases or subbases below asphalt or Portland cement concrete pavements, affords varying degrees of protection from exposure of the material(s) to the elements. The effect of this encapsulation is to reduce the "mobility" or the degree to which the material itself or soluble constituents contained in the material can migrate from its source into the adjacent environment.

Table 22-4. Waste and by-product pavement materials, applications, properties, and uses.

General Application	Material Substitutes	Physical Properties	Purpose	Amount Used[1]
Asphalt Concrete	Mineral Filler	Silt-size, less than 75 micron material	Fill voids in pavement structure	Constitutes 5 percent or less by weight when used in pavements
	Asphalt Aggregates	Gravel-sand size material, generally less than 19 mm (3/4 in) in size	Provide structural and bearing capacity for pavement	Generally constitutes 90 to 95 percent of the asphalt concrete structure by weight
	Asphalt Cement Modifiers	Silt-size or liquefied material	Introduced into asphalt cement to modify cement characteristics	Generally less than 25 percent of the asphalt cement, which constitutes about 1 percent of the asphalt concrete structure by weight
Portland Cement Concrete	Portland Cement Concrete Supplementary Cementitious Materials	Silt-size, less than 75 micron material	Introduced as additive or to replace portion of Portland cement; acts as pozzolan or cement	Generally replaces 15 to 50 percent by weight of cement, which constitutes about 1.5 to 5 percent of the Portland cement concrete structure by weight
	Portland Cement Concrete Aggregates	Gravel-sand size material, generally less than 19 mm (3/4 in) in size	Provide structural and bearing capacity for pavement	Generally constitutes 80 to 90 percent of the Portland cement concrete structure by weight

Table 22-4. Waste and by-product pavement materials, applications, properties, and uses (continued).

General Application	Material Substitutes	Physical Properties	Purpose	Amount Used[1]
Flowable Fill	Flowable Fill Aggregates	Fine-grained sand-silt material, generally less than 4.4 mm (1/4 in) in size	Provide structural and bearing capacity for fill	Generally constitutes 90 to 95 percent by weight of fill
	Flowable Fill Pozzolans or Initiators	Silt-sized, less than 75 micron material	Introduced as additive or replacement for Portland cement; acts as pozzolan or cement	Generally replaces 15 to 50 percent by weight of cement which constitutes about 1.5 to 5 percent of the fill structure
Stabilized Base	Stabilized Base Pozzolans or Initiators	Silt-sized, less than 75 micron material	Introduced as additive or replacement for Portland cement; acts as pozzolan or cement	Generally replaces 15 to 50 percent by weight of cement, which constitutes about 1.5 to 5 percent of the fill structure
	Stabilized Base Aggregates	Gravel-sand sized material, generally less than 19 mm (3/4 in) in size	Provide structural or bearing capacity for overlying burden	Generally comprises 80 to 90 percent of the base by weight
Unbound Aggregate and Fill	Granular Base	Gravel-sand sized material, generally less than 19 mm (3/4 in) in size	Provide structural or bearing capacity for overlying burden	Can constitute up to 100 percent by weight of the granular base or subbase structure
	Embankment and Fill Materials	Soil-like, sandy-silty material, generally less than 4.4 mm (1/4 in) in size	Provide structural or bearing capacity for overlying burden	Can constitute up to 100 percent by weight of structure of the embankment or fill structure

1. Note: The amounts presented represent the quantity of natural materials used in the specific application. The fraction of waste and by-product material use will be dependent on the mix design.

Aggregate and Fill Applications and Operations

The pavement applications addressed by these guidelines, including the use of waste and by-product materials as aggregates or fill material, can be divided into five major phases: (1) aggregate storage and processing, (2) material production (e.g., asphalt concrete), (3) construction, (4) service life, and (5) postservice life

Depending on the specific application, each of these phases involves one or more operations. When waste materials are used in an application, these operations could initiate the transfer of soluble metals, soluble organics, soluble solids, dust, or volatile constituents into the environment.

The remainder of this section provides illustrated summaries of the source operations, release mechanisms, and transfer media associated with the general pavement applications listed in Table 22-4, when a waste or by-product material is used as an aggregate substitute in that application. A list of measures that could be used to mitigate many of the release mechanisms is also included.

Aggregate Storage and Processing

Aggregate storage and processing operations are common elements to almost all pavement applications considered herein. Figure 22-1 presents an illustration of potential sources and transfer mechanisms that can be expected to result from operations associated with aggregate storage and processing activities.

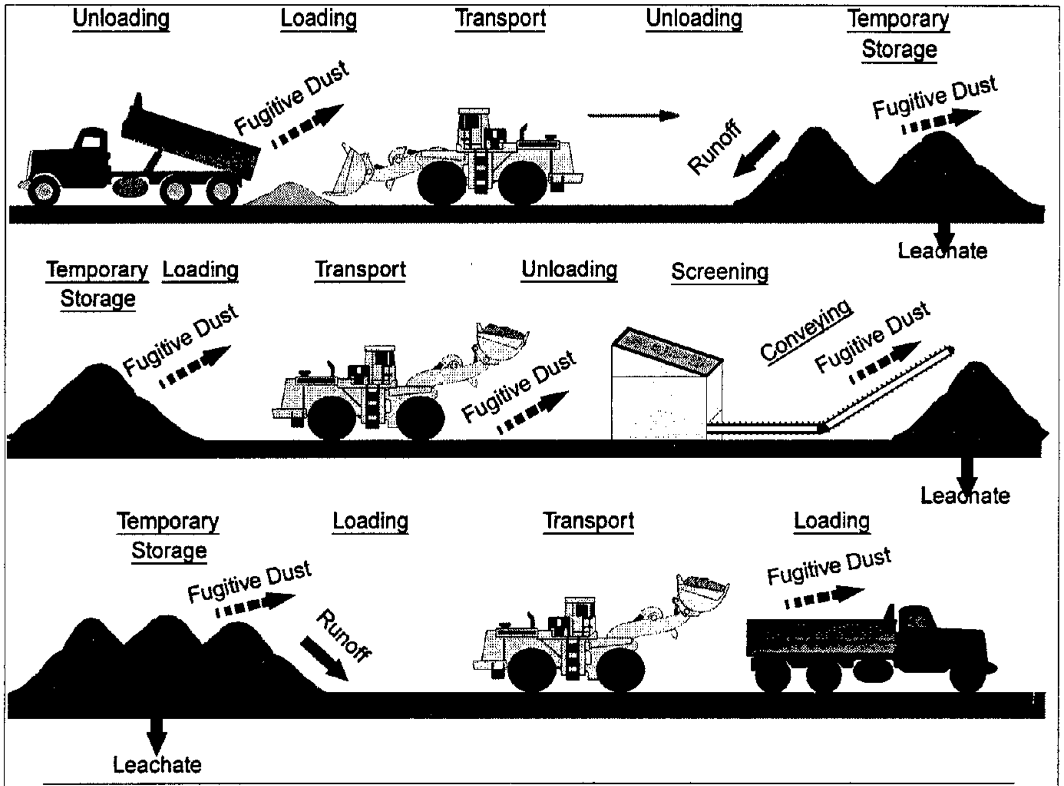
Operations and sources of potential concern include unloading, loading, on-site transport, temporary storage, screening, and conveying. Fugitive dust emissions could be generated in all of these operations, but can be mitigated to a great extent by the use of dust suppressants (e.g., moisture control) or by enclosing the operations.

Leachate and surface runoff discharges can be expected from outdoor stockpile operations. These discharges can be mitigated by covering the stockpiles and/or enclosing the operations.

Material Production, Construction, Service Life, and Postservice Life Operations

Hot Mix Asphalt Pavement

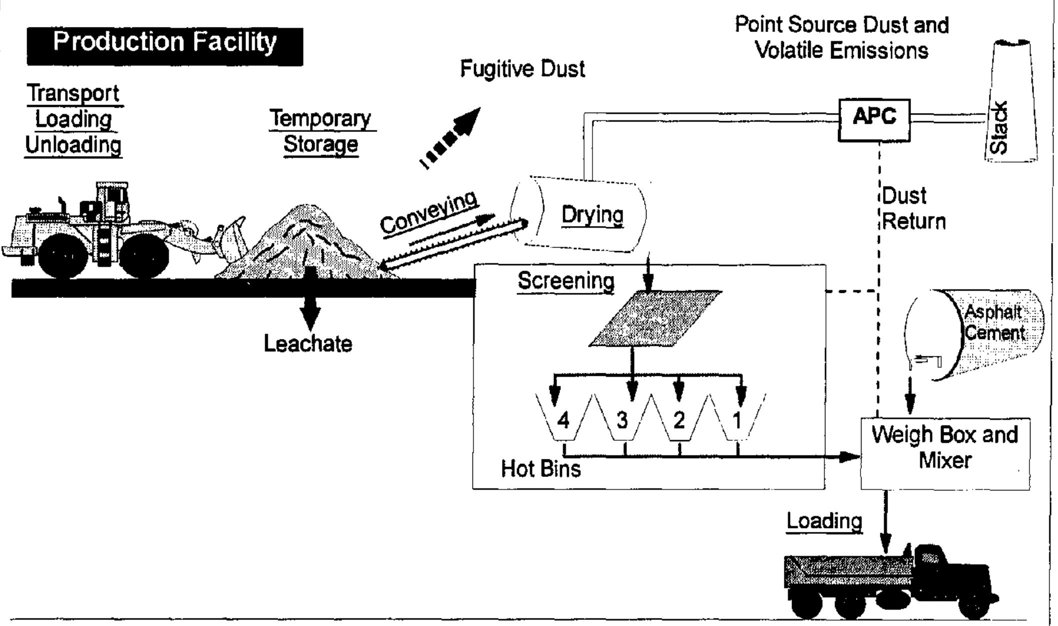
There are two types of hot mix asphalt production facilities that are commonly used to produce hot mix asphalt concrete: (1) batch plants and (2) drum-mix plants. Figure 22-2 depicts potential sources and transfer mechanisms that may result from operations at an asphalt production facility (batch plant). A drum-mix plant will have similar pathways.



Potential Source	Release Mechanism	Primary Transfer Media	Mitigating Measures
Unloading	Fugitive Dust	Air	Cover or Dust Suppressant
Loading	Fugitive Dust	Air	Cover or Dust Suppressant
Transport	Fugitive Dust	Air	Cover or Dust Suppressant
Temporary Storage	Fugitive Dust Leachate Runoff	Air Groundwater Surface Water	Cover or Dust Suppressant Cover Piles Cover Piles
Screening	Fugitive Dust	Air	Cover or Dust Suppressant
Conveying	Fugitive Dust	Air	Cover or Dust Suppressant

Figure 22-1. Storage and processing facility: operations, sources, transfer mechanisms, receptors, and mitigating measures.

In batch plants, fine and coarse aggregate are first dried and then screened. The screened aggregates are deposited into storage or hot bins. Hot bins are used to temporarily store the heated and screened aggregates, which are subsequently withdrawn, in predetermined proportions, to a mixer where the aggregates are combined and mixed with the asphalt cement. Hot screening and hot aggregate storage is provided in an enclosed structure. Emissions from the aggregate dryer are routed to an air pollution control system (typically a baghouse).



Potential Source	Release Mechanism	Primary Transfer Media	Mitigating Measures
Loading	Fugitive Dust	Air	Cover or Dust Suppressant
Transport	Fugitive Dust	Air	Cover or Dust Suppressant
Temporary Storage	Fugitive Dust	Air	Cover or Dust Suppressant
	Leachate	Groundwater	Cover Piles
	Runoff	Surface Water	Cover Piles
Drying	Point Source Dust	Air	Proper Dust Control Equipment
	Volatile Emissions	Air	Modify Operating Temperatures or APC Equipment
Screening	Point Source Dust	Air	Cover or Dust Suppressant
Conveying	Point Source Dust	Air	Cover or Dust Suppressant

Figure 22-2. Hot mix asphalt: production operations, sources, transfer mechanisms,receptors, and mitigating measures.

In drum-mix plants, cold aggregates of predetermined size are metered on a conveyor directly into a drum dryer where the aggregates are heated and mixed with the asphalt cement. There are no hot screens or hot bins in a drum-mix plant. Emissions from the drum dryer are routed to an air pollution control system, as in a batch plant.

Operations and sources of potential concern include stockpile storage, on-site truck and front-end loader traffic, loading, unloading, and conveying. The remaining operations (e.g., drying, screening, storage, mixing) occur in enclosed structures. Emissions from these latter operations (particularly drying) are typically routed to the air pollution control system. Air pollution control requirements (e.g., particulate, hydrocarbon, and carbon monoxide emissions) are defined by state air pollution control regulations.

Most of the release mechanisms at an asphalt production facility are dust related, resulting in air emissions that could affect local air quality or result in particulate deposition onto adjacent soils. Fugitive dust emissions will in most cases be a local worker environment issue, and can be mitigated using standard dust suppressant measures (e.g., moisture control).

Leachate or runoff discharges can be expected from outdoor stockpile operations, but can be mitigated by covering material stockpiles.

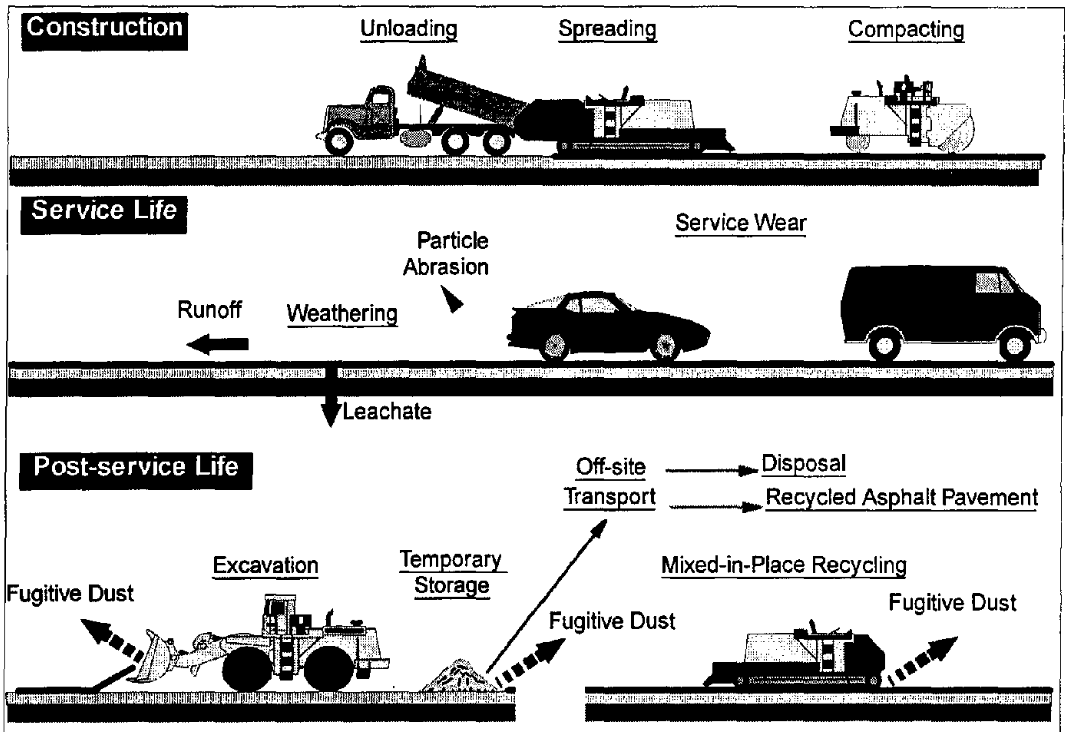
At a hot mix plant, there are no direct remedial methods for mitigating the release of highly volatile emissions without incorporating additional air pollution control equipment such as wet scrubbers. In most cases this may not be a practical solution. An alternative approach includes introducing materials into low-temperature zones within the facility to control the temperature of the material. In any event, the introduction of untried wastes or by-product materials that contain volatile constituents into an asphalt production facility will in most cases require testing to ensure that asphalt plant emissions do not exceed local air pollution control criteria.

Figure 22-3 depicts construction, service life, and postservice life sources and transfer mechanisms for hot mix asphalt pavement. Particle abrasion, runoff, and leaching are the primary release mechanisms that can be expected to occur during the pavement service life. Fugitive dust releases can be expected to occur during demolition, excavation, and pavement recycling operations; however, these activities are very short-lived and in most cases will have minimal impact.

During the service life of the pavement, the magnitude of any releases will depend almost exclusively on the mobility factors (e.g., solubility and transfer mechanisms) associated with pavement weathering and service wear. These factors will be much more prominent in a wearing surface, which is in direct contact with the wheel load and the elements, than a base course pavement.

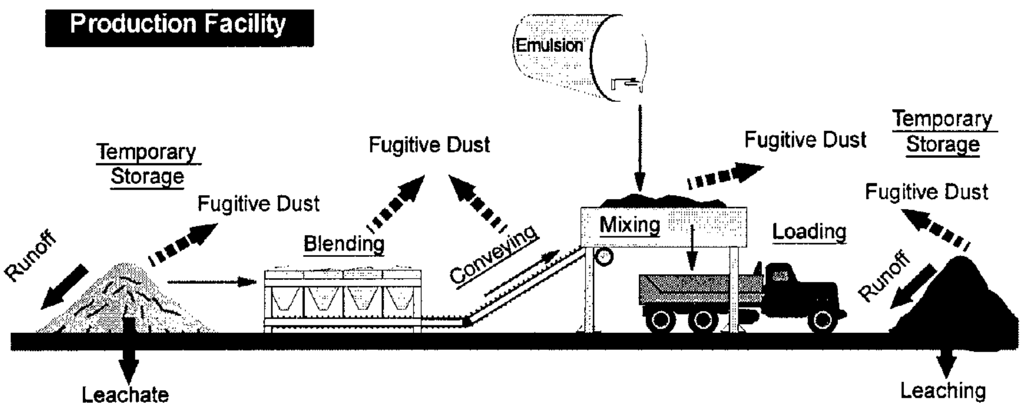
Cold Mix Asphalt Pavement

Cold mix production involves the storage, metering, conveying, and mixing of aggregates with a cold asphalt emulsion. Figure 22-4 depicts the potential sources and transfer mechanisms that could be expected to result from cold mix production operations.



Potential Source	Release Mechanism	Primary Transfer Media	Mitigating Measures
Weathering	Leachate Runoff	Groundwater Surface Water	Pavement Encapsulation Pavement Encapsulation
Service Wear	Particle Abrasion	Air	Pavement Encapsulation
Excavating	Particle Abrasion Fugitive Dust	Air	Dust Suppressants and Cleanup Dust Suppressants
Temporary Storage	Fugitive Dust Leachate Runoff	Air Groundwater Surface Water	Dust Suppressants Pavement Encapsulation Pavement Encapsulation
Mixed-in-Place Recycling	Fugitive Dust	Air	Dust Suppressants

Figure 22-3. Hot mix asphalt: construction, service life, and postservice life operations, sources, transfer mechanisms, receptors, and mitigating measures.



Potential Source	Release Mechanism	Primary Transfer Media	Mitigating Measures
Transport	Fugitive Dust	Air	Cover or Dust Suppressants
Unloading	Fugitive Dust	Air	Cover or Dust Suppressants
Loading	Fugitive Dust	Air	Cover or Dust Suppressants
Temporary Storage	Fugitive Dust Leachate Runoff	Air Groundwater Surface Water	Cover or Dust Suppressants Cover Piles Cover Piles
Blending	Fugitive Dust	Air	Cover or Dust Suppressants
Mixing	Fugitive Dust	Air	Cover or Dust Suppressants

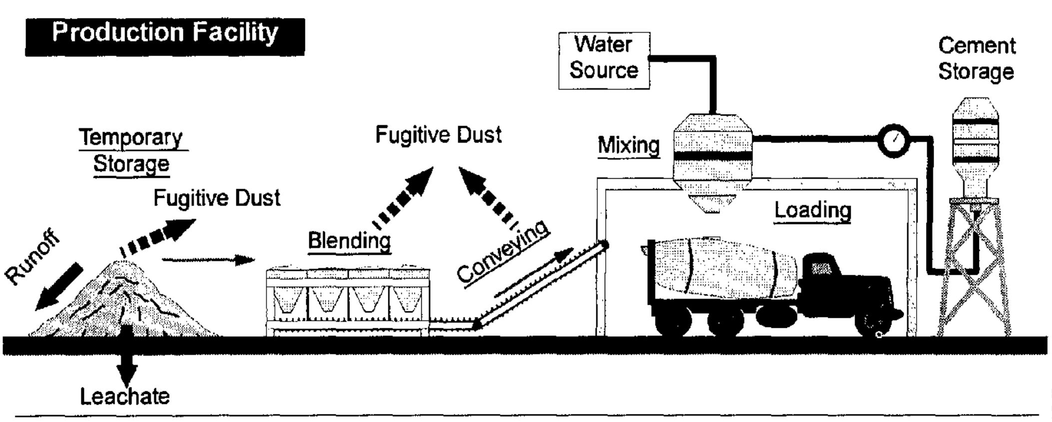
Figure 22-4. Cold mix asphalt: production operations, sources, transfer mechanisms, receptors, and mitigating measures.

Operations and sources of potential concern include on-site transport, loading, unloading, and blending. These operations could result in fugitive dust emissions. Outdoor stockpiles could generate leachate, runoff discharges, and fugitive dust emissions. Potential impacts and mitigating measures are similar to those for hot mix asphalt production operations. In cold mix operations, where aggregate drying is not included in the production process, there is reduced concern over volatile emissions.

Construction, service life, and postservice life operations and exposure pathways, and specific mobility issues, are similar to the pathways illustrated in Figure 22-3 for the hot mix pavement application.

Portland Cement Concrete Pavement

The production of Portland cement (ready mix) involves operations that include temporary storage, aggregate blending, conveying, mixing, and product loading. Figure 22-5 depicts the potential sources and transfer mechanisms that could be expected to result from operations associated with a Portland cement concrete production facility.

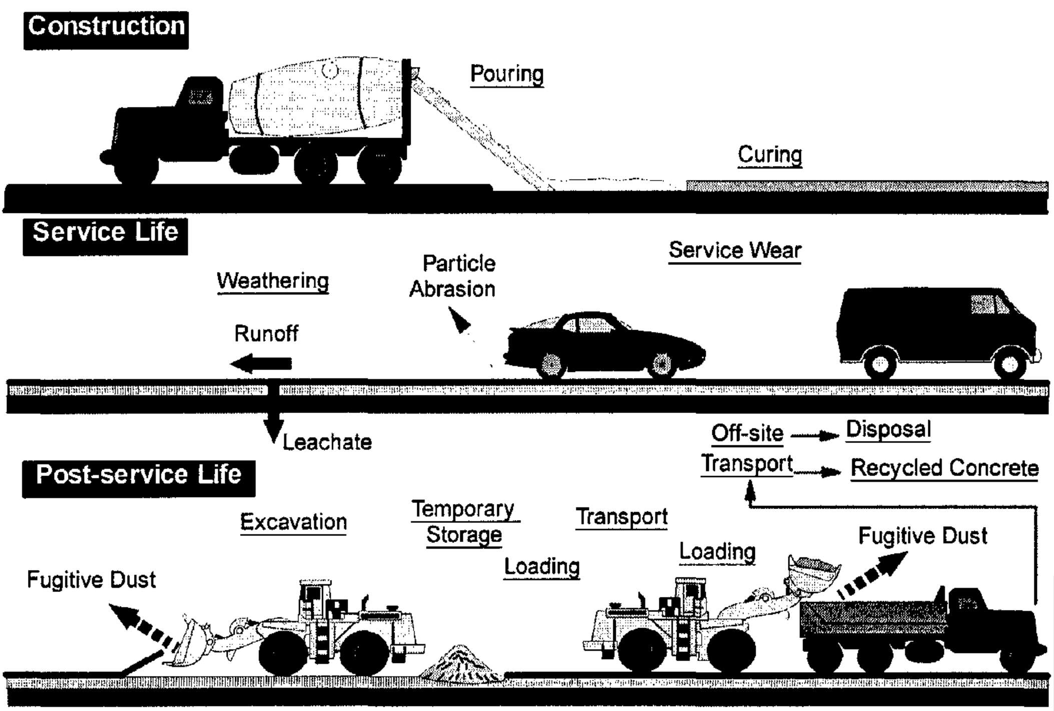


Potential Source	Release Mechanism	Primary Transfer Media	Mitigating Measures
Transport	Fugitive Dust	Air	Cover or Dust Suppressants
Unloading	Fugitive Dust	Air	Cover or Dust Suppressants
Loading	Fugitive Dust	Air	Cover or Dust Suppressants
Temporary Storage	Fugitive Dust	Air	Cover or Dust Suppressants
	Leachate	Groundwater	Cover Piles
	Runoff	Surface Water	Cover Piles
Blending	Fugitive Dust	Air	Cover or Dust Suppressants
Conveying	Fugitive Dust	Air	Cover or Dust Suppressants
Mixing	Fugitive Dust	Air	Cover or Dust Suppressants

Figure 22-5. Portland cement concrete pavement: production facility operations, sources, transfer mechanisms, receptors, and mitigating measures.

Most of the operations at the Portland cement production facilities and their release mechanisms and mitigating measures are similar to those at asphalt production and the aggregate storage and processing facilities. Local occupational dust exposure represents the primary potential environmental concern.

Figure 22-6 depicts construction, service life, and postservice life exposure pathways. Particle abrasion, runoff, and leaching are the primary release mechanisms that could be expected to occur during the pavement service life. Construction, service life, and postservice life mobility issues are similar to those issues addressed under the hotmix pavement review.



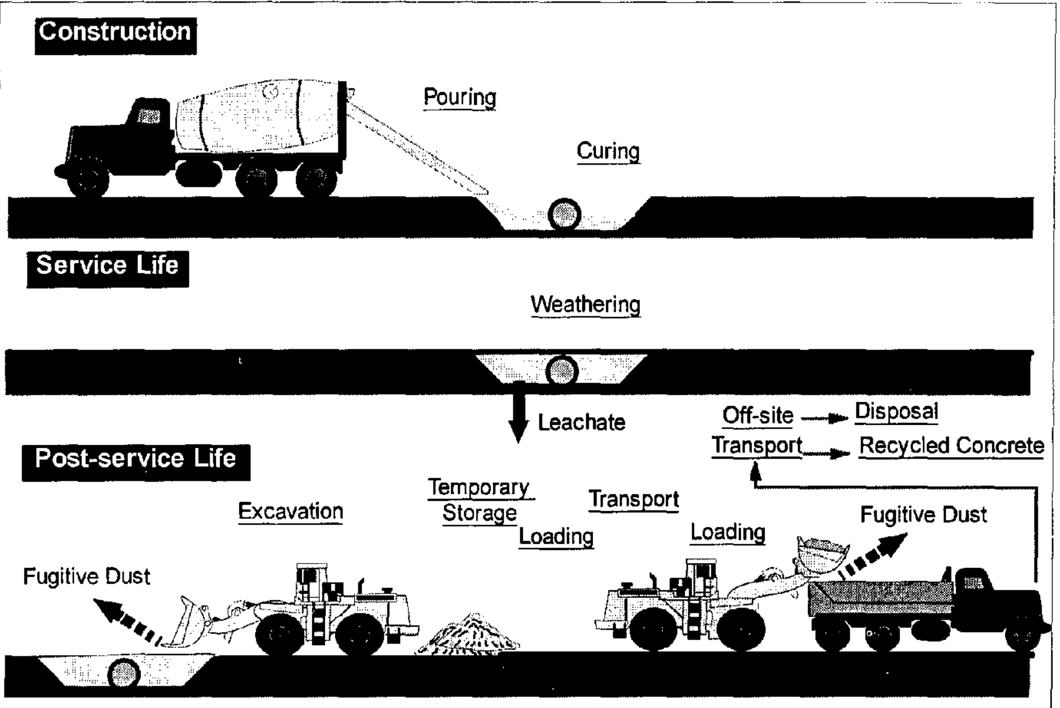
Potential Source	Release Mechanism	Primary Transfer Media	Mitigating Measures
Weathering	Leachate	Groundwater	Pavement Encapsulation
	Runoff	Surface Water	Pavement Encapsulation
Service Wear	Particle Abrasion	Air	Pavement Encapsulation
Excavating	Particle Abrasion	Air	Dust Suppressants and Cleanup
	Fugitive Dust	Air	Dust Suppressants
Loading	Fugitive Dust	Air	Dust Suppressants
Temporary Storage	Fugitive Dust	Air	Dust Suppressants
	Leachate	Groundwater	Cover Piles
	Runoff	Surface Water	Cover Piles

Figure 22-6. Portland cement concrete pavement: construction, service life and postservice life operations, sources, transfer mechanisms, receptors, and mitigating measures.

Fugitive dust releases can be expected during demolition, excavation, and pavement recycling operations, but once again, these are short-term activities from which minimal impact is expected.

Flowable Fill

Operations associated with the production of a flowable fill product and potential exposure pathways are very similar to those operations identified in Figure 22-5 for the production of a ready mix concrete. Figure 22-7 depicts construction, service life, and postservice life operations and potential sources and release mechanisms associated with these operations.



Potential Source	Release Mechanism	Primary Transfer Media	Mitigating Measures
Weathering	Leachate	Groundwater	Pavement Encapsulation
Excavating	Particle Abrasion	Air	Dust Suppressants and Cleanup
	Fugitive Dust	Air	Dust Suppressants
Loading	Fugitive Dust	Air	Dust Suppressants
Temporary Storage	Fugitive Dust	Air	Dust Suppressants
	Leachate	Groundwater	Cover Piles
	Runoff	Surface Water	Cover Piles

Figure 22-7. Flowable fill: construction, service life and postservice life operations, sources, transfer mechanisms, receptors, and mitigating measures.

Since flowable fill is normally used as a backfill material, leaching would be the primary release mechanism during the product's service life. Mobility issues will primarily depend on solubility and transport mechanisms associated with the flowable fill matrix, which should exhibit relatively low permeabilities.

Fugitive dust and leachate and runoff releases could be expected to occur during postservice life removal operations; however, these operations will be short-lived and minimal impact is expected from such operations.

Stabilized Base or Subbase

Production of a stabilized base material could occur at a central mixing facility, which would have operations similar to those outlined in Figure 22-4, for the cold mix production operation. Stabilized base production could also occur in the field where the aggregate or soil and stabilizing agent would be mixed, spread, and compacted. Figure 22-8 depicts the potential sources and transfer mechanisms that could be expected to result from field operations associated with stabilized base or subbase construction, service life, and postservice life operations.

Operations and sources of interest include field transport, loading, unloading, spreading, and compacting operations, all of which could generate fugitive dust emissions. Most of these fugitive dust emissions would be expected to result in localized impacts, primarily to the worker environment. Both construction and postservice life excavation operations are short-lived events and would not be expected to produce significant impacts.

Leachate discharges could occur during the service life of the material. Due to the presence of the overlying pavement, the mobility of the material or potential soluble components will be greatly reduced during the service life of the structure.

Stabilized Surface

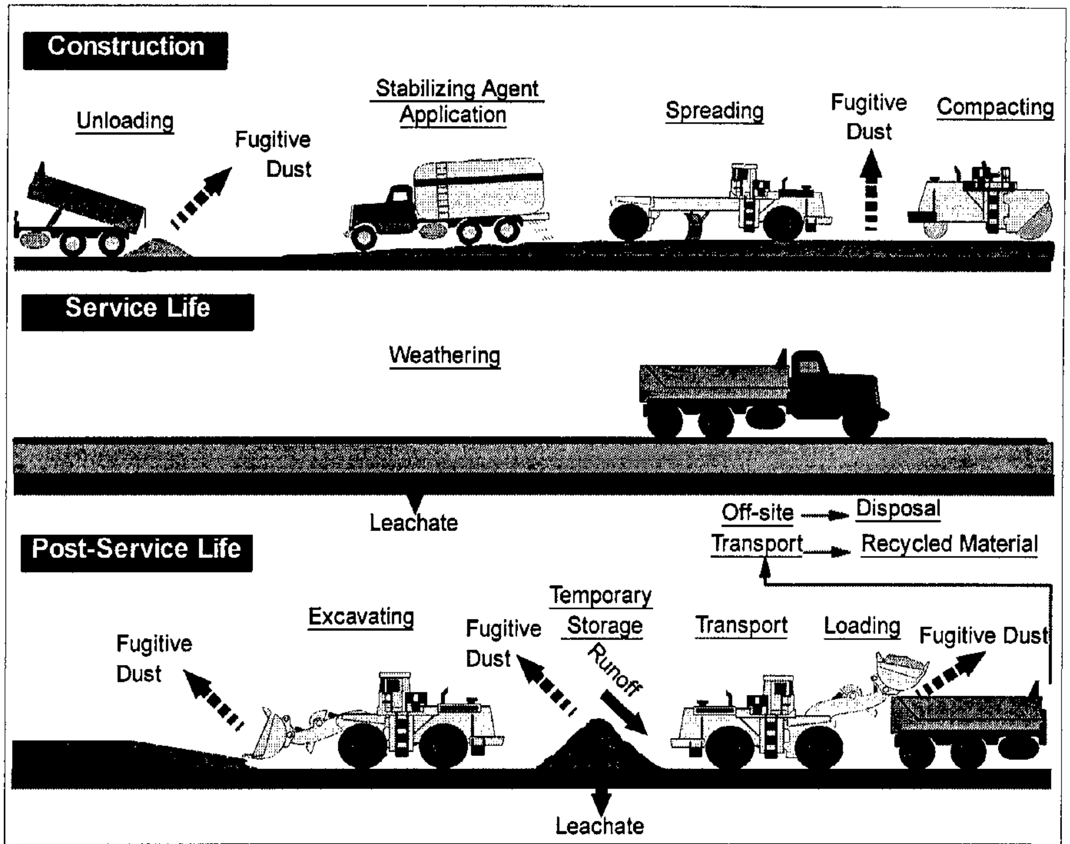
Surface treatments involve the use of aggregates and a binder (usually asphalt cement) to assist in providing an improved pavement surface. Operations involved in the production of a surface treatment are similar to paving operations, except the aggregate would be directly exposed to the surface during the service life of the pavement structure. As a result mobility considerations take on greater importance since the product will be directly exposed to the elements and traffic.

Figure 22-9 depicts the sources and potential release mechanisms that could be expected to result from construction, service life, and postservice life operation, respectively.

Operations during the pavement service life could be expected to be a source of particle abrasion and fugitive dust, leachate, and runoff discharges.

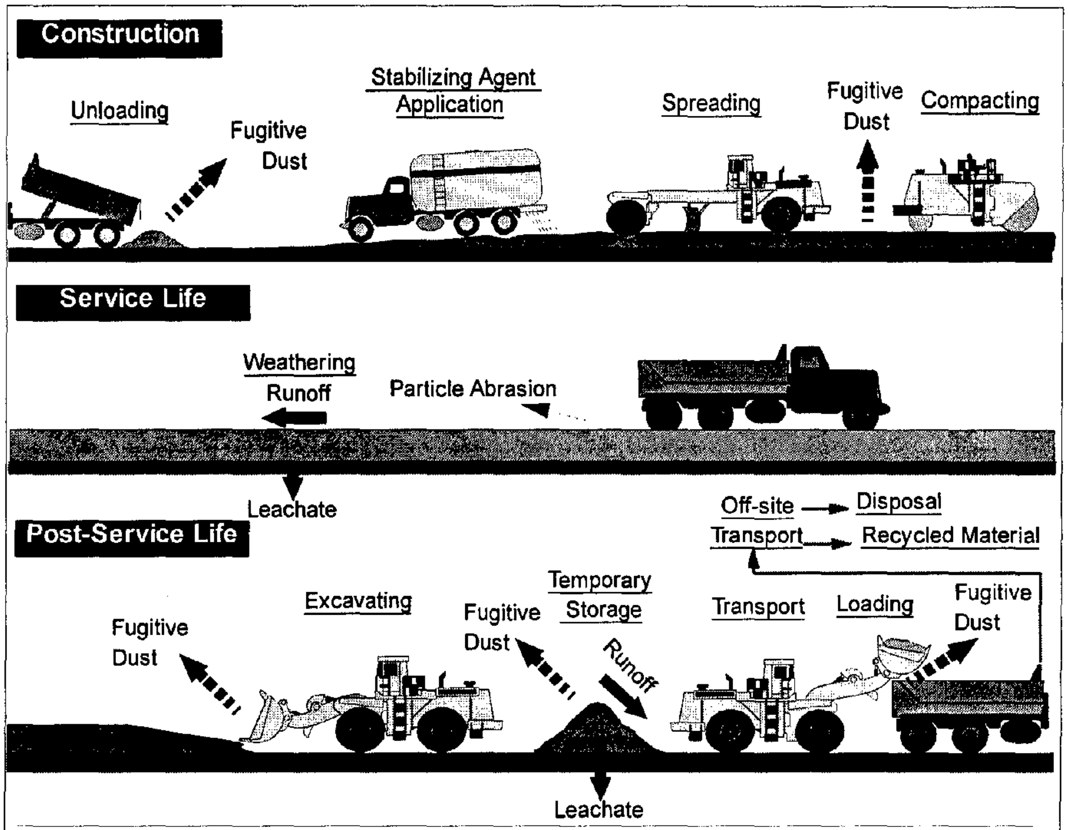
Granular Base

Granular base construction includes aggregate unloading, placement or spreading, and compacting operations. These operations are similar to those associated with a stabilized base as



Potential Source	Release Mechanism	Primary Transfer Media	Mitigating Measures
Transport	Fugitive Dust	Air	Dust Suppressants
Unloading	Fugitive Dust	Air	Dust Suppressants
Loading	Fugitive Dust	Air	Dust Suppressants
Temporary Storage	Fugitive Dust Leachate Runoff	Air Groundwater Surface Water	Dust Suppressants Cover Piles Cover Piles
Stabilizing Agent Application	Fugitive Dust	Air	Dust Suppressants
Spreading	Fugitive Dust	Air	Dust Suppressants
Compacting	Fugitive Dust	Air	Dust Suppressants
Weathering	Leachate	Groundwater	Pavement Encapsulation
Excavating	Fugitive Dust	Air	Dust Suppressants

Figure 22-8. Stabilized base: field construction service life and postservice life operations, sources, transfer mechanisms, receptors, and mitigating measures.



Potential Source	Release Mechanism	Primary Transfer Media	Mitigating Measures
Transport	Fugitive Dust	Air	Dust Suppressants
Unloading	Fugitive Dust	Air	Dust Suppressants
Temporary Storage	Fugitive Dust	Air	Dust Suppressants
	Leachate	Groundwater	Cover Piles
	Runoff	Surface Water	Cover Piles
Stabilizing Agent Application	Fugitive Dust	Air	Dust Suppressants
Spreading	Fugitive Dust	Air	Dust Suppressants
Compacting	Fugitive Dust	Air	Dust Suppressants
Service Wear	Particle Abrasion	Air	Pavement Encapsulation
Weathering	Leachate	Groundwater	Pavement Encapsulation
	Runoff	Surface Water	Pavement Encapsulation
Excavating	Fugitive Dust	Air	Dust Suppressants

Figure 22-9. Stabilized surface: field construction, service life and postservice life operations, sources, transfer mechanisms, receptors, and mitigating measures.

shown in Figure 22-8. In the construction of a granular base, however, no stabilizing agent is added to the aggregate or aggregate blend.

Figure 22-10 depicts the sources and potential release mechanisms that could be expected to result from operations associated with granular base construction, service life, and postservice life operations, respectively.

Operations during the short-lived construction period could generate fugitive dust emissions. During the service life of the base, leachate discharges could potentially occur, but in most cases will be mitigated by the overlying pavement. A granular base could be more readily exposed in high groundwater locations. Postservice life excavation operations of interest include excavation, temporary storage, and transport activities where fugitive dust releases and runoff and leachate discharges could occur; however, once again these short-lived operations would not be expected to produce significant impacts.

Embankments and Fills

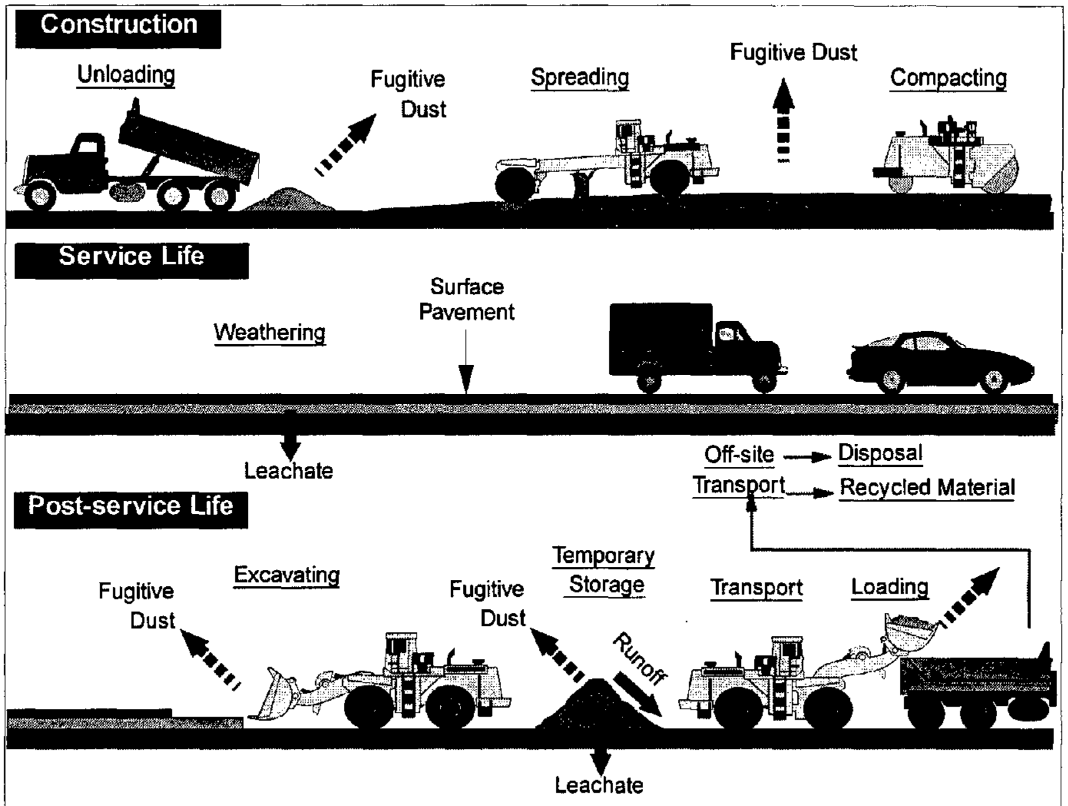
Embankment or fill construction, service life and postservice life operations, and sources and release mechanisms that could be expected to occur from these operations, are presented in Figure 22-11.

During short-lived construction operations, sources of interest include transport, unloading, loading, temporary storage, spreading, and fill compaction. Fugitive dust releases could be expected in almost all of these operations. Once again the primary concern in almost all cases would be the local worker environment. Leachate and surface runoff discharges could be expected from the temporary storage operations.

During the service life of the embankment or fill, runoff, leaching, and particle abrasion could be expected. Short-lived excavation, storage, transport, and loading operations represent sources of dust, runoff, and leachate discharges.

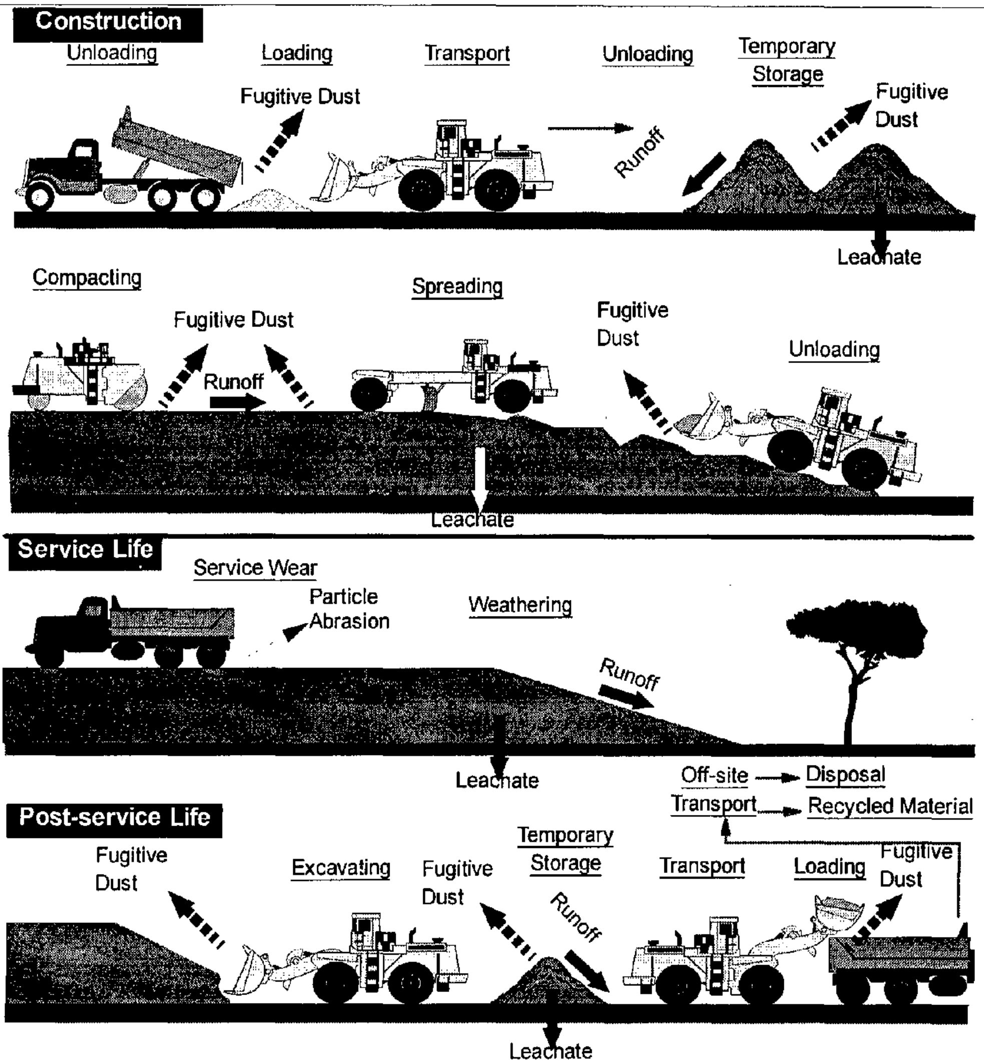
Postservice Life Recyclability Issues

Assessments of the environmental suitability of using waste and by-product material in pavement construction applications are complicated by the fact that most pavement products become new waste materials that must be disposed of or recycled after their initial service life, which generally lasts from approximately 5 to 20 years.



Potential Source	Release Mechanism	Primary Transfer Media	Mitigating Measures
Transport	Fugitive Dust	Air	Dust Suppressants
Unloading	Fugitive Dust	Air	Dust Suppressants
Loading	Fugitive Dust	Air	Dust Suppressants
Temporary Storage	Fugitive Dust Leachate Runoff	Air Groundwater Surface Water	Dust Suppressants Cover Piles Cover Piles
Spreading	Fugitive Dust	Air	Dust Suppressants
Compacting	Fugitive Dust	Air	Dust Suppressants
Weathering	Leachate	Groundwater	Pavement Encapsulation
Excavating	Fugitive Dust	Air	Dust Suppressants

Figure 22-10. Granular base: construction, service life and postservice life operations, sources, transfer mechanisms, receptors, and mitigating measures.



Potential Source	Release Mechanism	Primary Transfer Media	Mitigating Measures
Transport	Fugitive Dust	Air	Dust Suppressants
Unloading	Fugitive Dust	Air	Dust Suppressants
Loading	Fugitive Dust	Air	Dust Suppressants
Temporary Storage	Fugitive Dust	Air	Dust Suppressants
	Leachate Runoff	Groundwater Surface Water	Cover Piles Cover Piles
Spreading	Fugitive Dust	Air	Dust Suppressants
Compacting	Fugitive Dust	Air	Dust Suppressants
Service Wear	Particle Abrasion Fugitive Dust	Air Air	Pavement Encapsulation Pavement Encapsulation
Weathering	Fugitive Dust Leachate	Air Groundwater	Pavement Encapsulation Pavement Encapsulation
Excavating	Fugitive Dust	Air	Dust Suppressants

Figure 22-11. Embankment or fill: construction, service life and postservice life operations, sources, transfer mechanisms, receptors, and mitigating measures.

life. The present materials management strategy in most jurisdictions is to recycle as much of the excess pavement material as is economically practical. From an economic perspective, the maximum economic benefit of pavement material reuse is achieved when the pavement material is recycled into a product that will take maximum advantage of its inherent economic value. For example, concrete and hot mix aggregates are more "valuable" than granular base aggregates, which are more "valuable" than subbase aggregates, etc. As an example, the most cost-effective use for reclaimed asphalt pavement (RAP) may be to utilize the pavement in the production of new asphalt pavement, where the old aggregates and asphalt cement can reduce the quantity of new aggregates and asphalt cement required. Alternative uses, such as granular base, may not take advantage of the old asphalt cement present in the RAP, and therefore, this option may not represent the most cost-effective use, despite still being an important beneficial option.

In addition to this hierarchy, technical requirements (e.g., material specifications) will route excess materials to certain applications. For example, due to the asphalt present in RAP, its use in Portland cement concrete would not be advisable, and the use of embankment or fill material as an aggregate material in hot mix asphalt would probably not meet the more stringent specifications for aggregate to be used in hot mix asphalt.

Table 22-5 contains a matrix that indicates potential applications of excess materials from a demolished pavement in subsequent pavement construction. This matrix can help identify future options for evaluation.

Table 22-5. Waste and By-Product Material Recycling/Matrix.

Initial Application[1]	Potential Re-use Application[2]												
	HMAA	CMAA	SC	ACM	MF	PCCA	PCCMA	FFA	FFPI	SBSA	SBPI	GB	EF
ASPHALT PAVING													
Hot Mix Asphalt Aggregate	•	•	•							•		•	•
Cold Mix Asphalt Aggregate	•	•	•							•		•	•
Seal Coat or Surface Treatment Aggregate			•							•			•
Asphalt Cement Modifier	•	•	•							•		•	•
Mineral Filler	•	•	•							•		•	•
PORTLAND CEMENT CONCRETE													
Portland Cement Concrete Aggregate						•		•		•		•	•
Portland Cement Concrete Mineral Admixture						•		•		•		•	•
FLOWABLE FILL													
Flowable Fill Aggregate								•		•			•
Flowable Fill Pozzolan or Initiator								•		•			•
STABILIZED BASE													
Stabilized Base or Subbase Aggregate								•		•			•
Stabilized Base Pozzolan, Initiator or Additive								•		•			•
UNBOUND AGGREGATE AND FILL													
Granular Base or Subbase Aggregate								•		•		•	•
Embankment or Engineered Fill										•			•

Key:

HMAA = Hot Mix Asphalt Aggregate
CMAA = Cold Mix Asphalt Aggregate
SC = Seal Coat or Surface Treatment Aggregate
ACM = Asphalt Cement Modifier
MF = Mineral Filler
PCCA = Portland Cement Concrete Aggregate
PCCMA = Portland Cement Concrete Mineral Admixture
FFA = Flowable Fill Aggregate
FFPI = Flowable Fill Pozzolan or Initiator
SBSA = Stabilized Base or Subbase Aggregate
SBPI = Stabilized Base Pozzolan, Initiator of Additive
GB = Granular Base or Subbase Aggregate
EF = Embankment or Engineered Fill

1. Represents original waste or by-product material application.
2. Represents potential secondary uses of the excess material after the original service life. (Dots identify potential secondary application.)

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OVERVIEW

The decision of when or when not to use a waste or by-product material that is recovered for use in a pavement application, assuming that the material is capable of adequately performing in the proposed application, will in most cases depend on the cost of using the recovered material versus the cost of using a conventional material. As a result, recovered materials must be cost-competitive with conventional materials for their utilization to be practical. An exception to this rule occurs when such materials are mandated for use by legislation. In this case, the recovered material need not be cost-competitive with conventional materials, and the only competition is derived from alternate sources of the material.

While in the former case (nonmandated material), the competitive nature of the market process ensures that pavement costs using a recovered material will be equal to or less than costs associated with the use of conventional materials, in the latter case (mandated use), recovered material use can result in significant increases in pavement costs. In either case, a prospective user of a recovered material should obtain sufficient data to project the cost of using the proposed secondary material relative to the cost of conventional or other competitive materials.

There are three costs that are of interest when evaluating the cost of using a recovered material in pavement applications. These include:

1. The cost of the material.
2. The cost of installation when using the material.
3. The life-cycle cost of the pavement when using the material.

Each of the above costs could be relevant when examining the potential cost-benefits of using a recovered material. The specific situations where material, installation, and life-cycle costs would be relevant, and the components or elements that are needed to estimate these costs, are presented in the following sections.

COST OF MATERIAL

Once a waste or by-product material is introduced into the marketplace it will have a cost or price that a prospective user would pay to have the material delivered to a production or job site. The purchaser of the material could be a public agency, contractor, or material supplier. The seller would normally be the material generator or producer. If the recovered material is equivalent to a conventional material in expected design, construction, and performance, then the cost of material may be of primary interest when comparing the cost of using a secondary material with a conventional material.

The cost (delivered price) of a waste or by-product can be calculated as follows:

$$C_{DP} = P_{RM} + C_{PR} + C_{ST} + C_{LD} + C_{TR} + P \qquad (1)$$

where,

C_{DP} = Delivered price,
P_{RM} = Price of the raw material (F.O.B.),
C_{PR} = Cost of processing the material,
C_{ST} = Cost of stockpiling the material,
C_{LD} = Cost of loading the material,
C_{TR} = Cost of transporting the material, and
P = Profit.

The individual cost elements in Equation 1 are defined below:

Price of Raw Material - F.O.B. (P_{RM})

This cost is the value of the unprocessed material and is determined by the waste or by-product material generator or producer. As far as the material generator is concerned, the value of the material could be positive or negative. For example, if a recovered material generator must pay a $30 per ton fee for disposing of the material, then the material has a negative value of $30 per ton.

Cost of Processing the Material (C_{PR})

For many waste and by-product materials, some level of processing (screening, crushing, drying, etc.) may be required to convert the raw material into a product that is suitable for use in construction. There is an incremental cost for the required equipment and labor needed for such processing.

Cost of Stockpiling the Material (C_{ST})

Most construction materials are not used immediately or are incorporated into a construction product. Instead the material, even after processing, is usually stored or stockpiled for a period of time until it can be either delivered to a project site or used to make a finished product (such as concrete or asphalt). Associated site costs, and equipment and labor costs required to pick up, transport, and place the material into a stockpile, is an additional element in the total delivered price of the material.

Cost of Loading the Material (C_{LD})

After stockpiling, the material must be loaded into a transport vehicle for delivery, either to a project site or a production facility. There is also an incremental cost associated with the necessary labor and equipment required to load the material.

Cost of Transporting the Material (C_{TR})

Transportation costs must always be considered as part of the overall cost of a material. Depending on the distance the material or product has to be transported and the type of haul vehicle involved, the cost of transportation may constitute a significant percentage of the overall cost of a material or product, and in many cases is the determining factor as to whether it is practical to use the material. Most deliveries of recovered materials involve truck or rail hauling.

Profit (P)

A generator or producer of a waste or by-product material can profit from the sale of the material by either adding a profit to the cost of delivering the material to a prospective user, or by discounting the price of the raw material (if it has a negative value). For example, a generator with a material avoided disposal cost or material price (P_{RM}) of $30 per ton could give the material away and still accrue a $30 per ton benefit.

COST OF INSTALLATION

A prospective user may be more interested in the total cost of installation than simply the delivered price of the material. This would be the case when the cost of design, construction, and testing or inspection when using the recovered material differs from the cost of these items when using a conventional material. The cost of installation includes the delivered material price (C_{DP}), as well as the additional elements, outlined below.

The cost of installation when using a recovered material can be calculated as follows:

$$C_I = C_{DR} + C_C + T_{RP} \qquad (2)$$

where,

C_I = Cost of installation,
C_{DR} = Cost for design of application with the recovered material,
C_C = Cost for construction with the recovered material, and
T_{RP} = Cost of testing and inspection for the proposed application.

Equation 2 consists of the following elements:

Cost of Design of the Application with the Recovered Material (C_{DR})

For any highway construction application, there is a certain amount of time and effort involved in the design of the application, be it an embankment, base or subbase, pavement, or some form of appurtenance. In some cases, the time and effort required for design, when using recovered materials (C_{DR}) where design criteria may not be readily available, can be significantly greater than the effort needed to design conventional pavement applications.

Cost for Construction with the Recovered Material (C_C)

The construction cost when using a recovered material could differ from the cost of conventional materials if special procedures (e.g., preparation, compaction, etc.) are required when the recovered material is used.

Cost of Testing and Inspection for Recovered Material Applications (T_{RP})

For certain applications, the use of a recovered material could involve additional testing and inspection work. Use of a nonconventional material may require a greater degree of testing and field inspection requirements compared with that ordinarily required for the same application using a conventional material.

LIFE-CYCLE COST

The cost of the material itself and the cost of installation provide a prospective user with a comparative analysis of the cost of using a waste and by-product material versus a conventional material. If the introduction of a recovered material into a pavement application, however, alters the maintenance requirements or expected service life of the pavement, then a life-cycle cost analysis is necessary to provide a comparative assessment of the cost of using the recovered material versus a conventional material.

The life-cycle cost of a recovered material application can be calculated using a variety of economic approaches. The approach presented in this guideline is based on the calculation of an annual effective cost resulting from the proposed application. This annual cost can be calculated using the following equation:

$$A_{EC} = C_I \cdot CRF(i,n) + C_{AM} \tag{3}$$

where,

A_{EC} = Annual effective cost,
C_I = Cost of installation (see Eq. 2),
$CRF(i,n)$ = The capital recovery factor with an interest rate of i percent and a product life of n years, and
C_{AM} = Annual maintenance cost.

Annual Effective Cost (A_{EC})

The annual effective cost represents the sum of the annual amortized installation cost, over the life of the product, plus the annual maintenance cost, and represents the total annual cost of the pavement application.

Capital Recovery Factor ($CRF_{(I,N)}$)

The capital recovery factor (given a fixed interest rate and a product life) is a constant that, when multiplied by the installation cost, amortizes the initial installation cost over the life of the product, resulting in an effective annual installation cost.

The CRF is available in standard economic handbooks or on many spreadsheet programs or can be calculated using the following equation: $CRF = (i \cdot (1 + i)^n)/((1 + i)^n - 1))$.

Annual Maintenance Cost

The annual maintenance cost is determined by estimating, based on past experiences, the expected annual service costs associated with minor repairs that would be required over the life of the product.

To compare the life-cycle cost of an application when using a recovered material to a similar application with a conventional material requires that time periods be compared on an equivalent basis. A comprehensive analysis may require the introduction of pavement rehabilitation or new installation costs to achieve a suitable comparative analysis over equivalent time periods.

In many cases, due to the lack of long-term historical data regarding the expected service life and maintenance requirements associated with pavements containing secondary materials, life-cycle cost estimates are the most difficult of all costs to project.

APPLICATION DESCRIPTIONS

The primary design objective of the pavement engineer is to construct a pavement structure that will provide reliable, safe, and cost-effective service during its useful life. The introduction of nonconventional materials into a pavement structure imposes on the pavement engineer the responsibility to ensure that this primary design objective can still be achieved.

Six major pavement applications are described in this chapter. These applications, which are considered the primary applications where waste and by-product material may be incorporated, include asphalt concrete, Portland cement concrete, granular base, embankment or fill, stabilized base, and flowable fill applications. Other applications do exist (e.g., curb and gutter, medians, etc.), but are not within the scope of these guidelines at this time.

To provide more detailed information relative to the design objectives and the materials used in these applications, a general overview of each is provided in this chapter. This overview includes a description of the *conventional* component materials that are typically used in these applications, desired properties of these materials and the final composite product (where applicable), and standard ASTM and/or AASHTO test methods that are normally undertaken to verify the suitability of these materials and the final product.

To obtain more extensive information on specific applications, the reader is referred to the additional references which are presented at the end of each respective application description section.

INTRODUCTION

Asphalt concrete pavements consist of a combination of layers, which include an asphalt concrete surface constructed over a granular or asphalt concrete base and a subbase. The entire pavement structure, which is constructed over the subgrade, is designed to support the traffic load and distribute the load over the roadbed. Pavements can be constructed using hot mix or cold mix asphalt. Surface treatments are sometimes used during pavement construction. A surface treatment acts as a waterproof cover for the existing pavement surface and also provides resistance to abrasion by traffic.

Hot mix asphalt is a mixture of fine and coarse aggregate with asphalt cement binder that is mixed, placed, and compacted in a heated condition. The components are heated and mixed at a central plant and placed on the road using an asphalt spreader.

Cold mix asphalt is a mixture of emulsified asphalt and aggregate, produced, placed, and compacted at ambient air temperature. The use of cold mix asphalt is usually limited to relatively low-volume rural roads. For higher traffic applications, cold mix asphalt pavement usually requires an overlay of hot mix asphalt or surface treatment to resist traffic action. The components of cold mix asphalt can be mixed at a central plant or in-situ with a traveling mixer.

Surface treatments consist of an application (or sometimes multiple applications) of emulsified or liquid asphalt and select aggregate, placed over a prepared granular base or existing surface. Following placement of the aggregate, the mixture is rolled and compacted to provide a drivable, dust-free surface. This type of pavement is common on light- to medium- volume roads that may or may not already have an existing bituminous surface.

MATERIALS

The components of asphalt concrete include asphalt aggregate and asphalt binder. Mineral filler is sometimes added to hot mix asphalt concrete.

Asphalt Aggregate

Aggregates used in asphalt mixtures (hot mix asphalt, cold mix asphalt, surface treatments) comprise approximately 95 percent of the mix by mass. Proper aggregate grading, strength, toughness, and shape are needed for mixture stability.

Asphalt Binder

The asphalt binder component of an asphalt pavement typically makes up about 5 to 6 percent of the total asphalt mixture, and coats and binds the aggregate particles together. Asphalt cement is used in hot mix asphalt. Emulsified asphalt, which is asphalt cement dispersed in water with the aid of an emulsifying agent, is used as the binder in surface treatments and cold mix asphalt pavements ("cutback" asphalt, which is asphalt cement dispersed in solvent, has been used in the past but is not normally used at present). The properties of binders are often improved or enhanced by using additives or modifiers to improve adhesion (stripping resistance), flow, oxidation characteristics, and elasticity. Modifiers include oil, filler, powders, fibers, wax, solvents, emulsifiers, wetting agents, as well as other proprietary additives.

Mineral Filler

Mineral filler consists of very fine, inert mineral matter that is added to the hot mix asphalt to improve the density and strength of the mixture. Mineral fillers make up less than 6 percent of the hot mix asphalt concrete by mass, and generally less than about 3 percent. A typical mineral filler completely passes a 0.060 mm (No. 30) sieve, with at least 65 percent of the particles passing the 0.075 mm (No. 200) sieve.

MATERIAL PROPERTIES AND TESTING METHODS

Asphalt Aggregate

Since aggregates used in bituminous mixtures (hot mix asphalt, cold mix asphalt, surface treatments) comprise approximately 95 percent of the mixture by mass and roughly 80 percent by volume, the aggregate material(s) used in asphalt concrete have a profound influence on the properties and performance of the mixture. The following is a listing and brief comment on some of the more important properties for aggregates that are used in asphalt paving mixes:

- <u>Gradation</u> – the size distribution of the aggregate particles should be a combination of sizes that results in the optimum balance of voids (density) and pavement strength.

- <u>Particle Shape</u> – aggregate particles should be angular and nearly equidimensional or cubical in shape to minimize surface area. Flat or elongated particles should be avoided.

- <u>Particle Texture</u> – particles should have a rough rather than smooth texture to minimize the stripping of asphalt cement.

- Particle Strength – particles should be of sufficient strength to resist degradation or breakdown under compaction or traffic.

- Durability – particles must be durable enough to remain intact under variable climatic conditions and/or chemical exposure.

- Specific Gravity – the specific gravity of an aggregate is needed in order to properly design and proportion an asphalt mix.

- Absorption – the absorption of an aggregate refers to the amount of void spaces within a particle that may be filled with asphalt binder (or air or water), and is a measure of the tendency of an aggregate to absorb asphalt. The higher the absorption, the more asphalt cement will be needed.

- Unit Weight – the unit weight of an aggregate is an indicator of the compacted density of an asphalt paving mix containing this aggregate and the pavement yield (the volume of pavement that will be required for a given pavement mass).

- Volume Stability – certain aggregates may undergo volumetric expansion following prolonged exposure to moisture, deicing salts, etc., which may contribute to popouts, raveling, and random cracking in asphalt pavements.

- Deleterious Components – some aggregates may contain harmful amounts of potentially reactive components (shale, chert, sulfates, alkalis, expansive silicates, etc.), which may contribute to popouts, raveling, and cracking in pavements.

Table 24-1 provides a list of standard test methods that are used to assess the suitability of conventional mineral aggregates for use in asphalt paving applications.

Asphalt Binder

Although the asphalt binder component typically comprises approximately 5 to 6 percent by mass of an asphalt paving mixture, the selection of the proper grade of asphalt (asphalt cement or emulsion) for the traffic and climatic conditions to which the paving mixture is to be exposed is essential to the performance of the mix. Some of the more important properties of asphalt

Table 24-1. Asphalt paving aggregate test procedures.

Property	Test Method	Reference
General Specifications	Coarse Aggregate for Bituminous Paving Mixtures	ASTM D692
	Fine Aggregates for Bituminous Paving Mixtures	ASTM D1073/ AASHTO M 29
	Steel Slag Aggregates for Bituminous Paving Mixtures	ASTM D5106
	Aggregate for Single or Multiple Surface Treatments	ASTM D1139
	Crushed Aggregate For Macadam Pavements	ASTM D693
Gradation	Sieve Analysis of Fine and Coarse Aggregates	ASTM C136/ AASHTO T27
	Sizes of Aggregate for Road and Bridge Construction	ASTM D448/ AASHTO M43
Particle Shape	Index of Aggregate Particle Shape and Texture	ASTM D3398
	Flat and Elongated Particles in Coarse Aggregate	ASTM D4791
	Uncompacted Void Content of Fine Aggregate (As Influenced by Particle Shape, Surface Texture, and Grading) (Test is part of SHRP Superpave Level 1 design procedure for hot mix asphalt)	ASTM C1252/ ASHTO TP33
Particle Texture	Accelerated Polishing of Aggregates Using the British Wheel (Not widely recognized in North America)	ASTM D3319/ AASHTO T279
	Insoluble Residue in Carbonate Aggregates (Indirect measure of resistance of aggregate to wear, by determining amount of carbonate rock present)	ASTM D3042
	Centrifuge Kerosine Equivalent (Only used as part of the Hveem mix design procedure)	ASTM D5148
Particle Strength	Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine	ASTM C535
	Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine	ASTM C131/ AASHTO T96
	Degradation of Fine Aggregate Due to Attrition	ASTM C1137

Table 24-1. Asphalt paving aggregate test procedures (continued).

Property	Test Method	Reference
Durability	Aggregate Durability Index	ASTM D3744/ AASHTO T210
	Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate	ASTM C88/ AASHTO T104
	Soundness of Aggregates by Freezing and Thawing	AASHTO T103
Specific Gravity and Absorption	Specific Gravity and Absorption of Coarse Aggregate	ASTM C127/ AASHTO T85
	Specific Gravity and Absorption of Fine Aggregate	ASTM C128/ AASHTO T84
Unit Weight	Unit Weight and Voids in Aggregate	ASTM C29/C29M/ AASHTO T19
Volume Stability	Potential Expansion of Aggregates from Hydration Reactions (Developed to measure expansion potential of steel slag aggregates)	ASTM D4792
Deleterious Components	Sand Equivalent Value of Soils and Fine Aggregate (Indirect measure of clay content of aggregate mixes)	ASTM D2419
	Clay Lumps and Friable Particles in Aggregates	ASTM C142

cement that are used to distinguish between different cements and to evaluate their quality include:

- Penetration – a measure of the relative softness or hardness of an asphalt cement (or emulsion) at a given temperature.

- Viscosity – a measure of the resistance of an asphalt cement to flow at a given temperature.

- Ductility – a measure of the ability of an asphalt cement to undergo elongation under tensile stress at a given temperature.

- Incompatibility – a measure of phase separation of the components of polymer-modified asphalt binders during storage and use. Such a separation is undesirable since it results in significant variation in the properties of the binder and the asphalt in which it is used.

Table 24-2 provides a list of standard test methods used to characterize asphalt binder properties.

Table 24-2. Asphalt binder test procedures.

Property	Test Method	Reference
General Specifications	Recovery of Asphalt from Solution by the Abson Method	ASTM D1856
	Graded Asphalt Cement for Use in Pavement Construction	ASTM D946
	Graded Asphalt Cement for Use in Pavement Construction	ASTM D3381
	Emulsified Asphalt	ASTM D977
Rheology	Penetration of Bituminous Materials	ASTM D5
	Preparation of Viscosity Blends for Recycled Bituminous Materials	ASTM D4887
	Kinematic Viscosity of Asphalts	ASTM D2170
	Ductility of Bituminous Materials	ASTM D113
	Effect of Heat/Air on Asphaltic Materials by Thin-Film Oven Test	ASTM D1754
	SHRP Level 1 Binder Testing	SHRP Mix Design Manual A-407
Incompatibility	Storage Stability Test	Shell Bitumen Industrial Handbook, 1995

Mineral Filler

Mineral fillers consist of finely divided mineral matter such as rock dust, slag dust, hydrated lime, hydraulic cement, fly ash, loess, or other suitable mineral matter.

Mineral fillers serve a dual purpose when added to asphalt mixes. The portion of the mineral filler that is finer than the thickness of the asphalt film and the asphalt cement binder form a mortar or mastic that contributes to improved stiffening of the mix. The particles larger than the thickness of the asphalt film behave as mineral aggregate and hence contribute to the contact points between individual aggregate particles. The gradation, shape, and texture of the mineral filler significantly influence the performance of hot mix asphalt.

Some of the more important properties of mineral filler used in asphalt concrete applications are as follows:

- Gradation – mineral fillers should have 100 percent of the particles passing 0.60 mm (No. 30 sieve), 95 to 100 percent passing 0.30 mm (No. 40 sieve), and 70 percent passing 0.075 mm (No. 200 sieve).

- Plasticity – mineral fillers should be nonplastic so the particles do not bind together.

- Deleterious Materials – the percentage of deleterious materials such as clay and shale in the mineral filler must be minimized to prevent particle breakdown.

Table 24-3 provides a listing of applicable test methods containing criteria that are used to characterize the suitability of conventional filler materials for use in asphalt paving applications.

Table 24-3. Mineral filler test procedures.

Property	Test Method	Reference
General Specifications	Mineral Filler for Bituminous Paving Mixtures	ASTM D242/ AASHTO M 17
Gradation	Sieve Analysis of Mineral Filler for Road and Paving Materials	ASTM D546
Plasticity	Liquid Limit, Plastic Limit, and Plasticity Index of Soils	ASTM D4315
Deleterious Materials	Sand Equivalent Value of Soils and Fine Aggregate (Indirect measure of clay content of aggregate mixes)	ASTM D2419

ASPHALT CONCRETE MATERIAL

The mix proportions for a properly compacted asphalt concrete paving mixture are determined in the laboratory during mix design testing. The ability of a properly proportioned asphalt paving mix to resist the potentially damaging effects of the asphalt binder stripping from the aggregate particles is also routinely evaluated in the laboratory. To perform properly in the field, a well-designed asphalt paving mixture must be placed within the proper temperature range and must be adequately compacted. Asphalt concrete paving mixtures should be evaluated for the following properties:

- Stability – the load that a well-compacted paving mixture can accept before failure. Sufficient mix stability is required to satisfy the demands of traffic without distortion or displacement.

- Flow – the maximum diametric compressive strain measured at the instance of failure. The ratio of Marshall stability to flow approximates the mix's load-deformation characteristics and therefore indicates the material's resistance to permanent deformation in service.

- Air Voids – the percentage of void spaces within the aggregate-binder matrix that are not filled with binder. Sufficient voids should be provided to allow for a slight amount of additional compaction under traffic and a slight amount of asphalt expansion due to temperature increases, without flushing, bleeding, or loss of stability.

- Stripping Resistance – the ability of a paving mixture to resist the loss of tensile strength due to stripping of the asphalt cement from the aggregate. Low resistance to stripping could result in mix disintegration.

- Resilient Modulus – a measure of the stiffness of a well-compacted paving mixture under prescribed conditions of load application. A mix having a low resilient modulus would be susceptible to deformation, whereas a high resilient modulus indicates a brittle mixture.

- Compacted Density – the maximum unit weight or density of a properly designed paving mixture compacted under prescribed laboratory compaction procedures.

- Unit Weight – a measure of the density of a paving mixture compacted in the field in accordance with project specifications.

Table 24-4 provides a list of standard laboratory tests that are presently used to evaluate the mix design or expected performance of paving mixes.

Table 24-4. Asphalt paving material test procedures.

Property	Test Method	Reference
Stability and Flow Characteristics (also air voids)	Marshall Method	AASHTO T245
	Hveem Method	AASHTO T246, T247
	Asphalt Institute Recommended Cold Mix Method	Asphalt Institute Cold Mix Manual
	Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus	ASTM D1559
Stripping Resistance	Immersion - Marshall Method	ASTM D4867
	Immersion - Marshall Method	AASHTO T283 (Modified Lottman Method)
Resilient Modulus	Superpave Mix Design	Asphalt Institute Superpave Series No. 1 (SP-1)
		Asphalt Institute Superpave Series No. 2 (SP-2)
Unit Weight	Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures	ASTM D2041
Compacted Density	In-Place Density of Compacted Bituminous Paving Mixtures	ASTM D2950

Recent developments in asphalt pavement design research which was conducted under the Strategic Highway Research Program (SHRP), has resulted in the development of a new asphalt mix design procedure, referred to as Superpave (Superior Performing Asphalt Pavement Design Procedure). Where the traditional mix design approach (using Marshall mix or Hveem design methods) was based on empirical laboratory design procedures, the Superpave mix design approach represents an improved system for specifying asphalt binder and mineral aggregates, developing an asphalt mixture design, and analyzing and establishing pavement performance prediction. The system includes an asphalt binder specification (performance graded binders), a hot mix asphalt design and analysis system, and computer software that integrates the system components. The unique feature of the Superpave system is that it is a performance-based specification approach, with the tests and analyses having direct relationship to field performance.

Superpave mix design and analysis is performed at one of three increasingly rigorous levels of performance. Superpave Level 1 is an improved materials selection and volumetric mix design procedure; Level 2 uses the same volumetric mix design procedure as Level 1 as a starting point, in conjunction with a battery of tests to predict the mix performance; and Level 3 involves a more comprehensive array of tests to achieve a more reliable level of performance prediction. At present, only the performance-graded asphalt binder specification and Superpave Level 1 approach has been finalized, with the performance prediction models used in the Level 2 and Level 3 procedures still being validated.

Users are referred to the Asphalt Institute Superpave Series No. 1 and No. 2 publications listed in the reference section for detailed information on the Superpave mix design equipment and test methods and on the performance-graded asphalt binder requirements:

REFERENCES FOR ADDITIONAL INFORMATION

AASHTO Guide for the Design of Pavement Structures. American Association of State Highway and Transportation Officials, Washington, DC, 1993.

Basic Asphalt Emulsion Manual. Asphalt Institute, Manual Series No. 19, Lexington, Kentucky.

Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types. Manual Series No. 2 (MS-2), Sixth Edition, Asphalt Institute, Lexington, Kentucky, 1994.

Morgan, P. and A. Mulder. *The Shell Bitumen Industrial Handbook.* Shell Bitumen, Riversdell House, Surrey, U.K., 1995.

Performance Graded Asphalt Binder Specification and Testing. Superpave Series No. 1 (SP-1), Asphalt Institute, Lexington, Kentucky.

Superpave Level 1 Mix Design. Superpave Series No. 2 (SP-2), Asphalt Institute, Lexington, Kentucky.

PORTLAND CEMENT CONCRETE PAVEMENT

Application Description

INTRODUCTION

Portland cement concrete (PCC) pavements (or rigid pavements) consist of a PCC slab that is usually supported by a granular or stabilized base, and a subbase. In some cases the PCC slab may be overlaid with a layer of asphalt concrete.

Portland cement concrete is produced at a central plant and transported to the job site in transit mixers or batched into truck mixers directly and then mixed at the project site. In either case, the PCC is then dumped, spread, leveled, and consolidated, generally using concrete slip-form paving equipment.

MATERIALS

Basic components of PCC include coarse aggregate (crushed stone or gravel), fine aggregate (usually natural sand), Portland cement, and water. The aggregate functions as a filler material, which is bound together by hardened Portland cement paste formed by chemical reactions (hydration) between the Portland cement and water. In addition to these basic components, supplementary cementitious materials and chemical admixtures are often used to enhance or modify properties of the fresh or hardened concrete.

Concrete Aggregate

The coarse and fine aggregates used in PCC comprise about 80 to 85 percent of the mix by mass (60 to 75 percent of the mix by volume). Proper aggregate grading, strength, durability, toughness, shape, and chemical properties are needed for concrete mixture strength and performance.

Portland Cement and Supplementary Cementitious Materials

Portland cements are hydraulic cements that set and harden by reacting with water, through hydration, to form a stonelike mass. Portland cement typically makes up about 15 percent of the PCC mixture by weight. Portland cement is manufactured by crushing, milling, and blending selected raw materials containing appropriate proportions of lime, iron, silica, and alumina. Most Portland cement particles are less than 0.045 mm (No. 325 sieve) in diameter.

Portland cement combined with water forms the cement paste component of the concrete mixture. The paste normally constitutes about 25 to 40 percent of the total volume of the concrete. Air is also a component of the cement paste, occupying from 1 to 3 percent of the total concrete volume, up to 8 percent (5 to 8 percent typical) in air entrained concrete. In terms of absolute volume, the cementing materials make up between about 7 and 15 percent of the mix, and water makes up 14 to 21 percent.

Supplementary cementitious materials are sometimes used to modify or enhance cement or concrete properties. They typically include pozzolanic or self-cementing materials. Pozzolanic materials are materials comprised of amorphous siliceous or siliceous and aluminous material in a finely divided (powdery) form, similar in size to Portland cement particles, that will, in the presence of water, react with an activator, typically calcium hydroxide and alkalis, to form compounds possessing cementitious properties. Descriptions of various kinds of pozzolans and their specifications are provided in ASTM C618. Self-cementing materials are materials that react with water to form hydration products without any activator.

Supplementary cementitious materials can affect the workability, heat released during hydration, the rate of strength gain, the pore structure, and the permeability of the hardened cement paste.

Coal fly ash that is produced during the combustion of bituminous coals exhibits pozzolanic properties. Silica fume is also a pozzolanic material consisting almost entirely (85 percent or more) of very fine particles (100 times smaller than Portland cement) that are highly reactive.

Coal fly ash produced during the combustion of subbituminous coal exhibits self-cementing properties (no additional activators, such as calcium hydroxide, are needed). Similarly, ground granulated blast furnace slag reacts with water to form hydration products that provide the slag with cementitious properties.

Coal fly ash and ground granulated blast furnace slag can be blended with Portland cement prior to concrete production or added separately to a concrete mix (admixture). Silica fume is used exclusively as an admixture.

Chemical and Mineral Admixtures

An admixture is a material, other than Portland cement, water and aggregate, that is used in concrete as it is mixed to modify the fresh or hardened concrete properties. Chemical admixtures fall into three basic categories. They include water-reducing agents, air-entraining agents, and setting agents. Chemical admixtures for concrete are described in ASTM C494.

Water-reducing agents are chemicals that are used to reduce the quantity of water that needs to be added to the mix, at the same time producing equivalent or improved workability and strength.

Air entrainment increases the resistance of concrete to disintegration when exposed to freezing and thawing, increases resistance to scaling (surface disintegration) that results from deicing chemicals, increases resistance to sulfate attack, and reduces permeability. Air entrainment can be accomplished by adding an air-entraining admixture during mixing. There are numerous commercial air entraining admixtures manufactured. Descriptions and specifications are described in ASTM C260.

Setting agents can be used to either retard or accelerate the rate of setting of the concrete. Retarders are sometimes used to offset the accelerating effect of hot weather or to delay the set when placing of the concrete may be difficult. Accelerators are used when it is desirable to gain strength as soon as possible to support design loads. Calcium chloride is an active material that is most commonly used as an accelerator. Setting agents (retarders and accelerators) are described in greater detail in ASTM C494.

MATERIAL PROPERTIES AND TESTING METHODS

Concrete Aggregate

Since aggregates used in concrete mixtures comprise approximately 80 to 85 percent of the concrete mixture by mass (60 to 75 percent of the concrete mixture by volume), the aggregate materials used have a profound influence on the properties and performance of the mixture in both the plastic and hardened states. The following is a listing and brief comment on some of the more important properties for aggregates that are used in concrete paving mixtures:

- Gradation – the size distribution of the aggregate particles affects the relative proportions, cementing materials and water requirements, workability, pumpability, economy, porosity, shrinkage, and durability. The size distribution of the aggregate particles should be a combination of sizes that results in a minimum of void spaces.

- Absorption – the absorption and surface moisture condition of aggregates must be determined so that the net water content of the concrete can be controlled.

- Particle Shape and Surface Texture – the particle shape and surface texture of both coarse and fine aggregates have a significant influence on the properties of the plastic concrete. Rough textured, angular, or elongated particles require more water to produce workable concrete than smooth, rounded, compact aggregates, and as a result, these aggregates require more cementing materials to maintain the same water-cement ratio. Angular or poorly graded aggregates may result in the production of concrete that is more difficult to pump and also may be more difficult to finish. The hardened concrete strength will generally increase with increasing coarse aggregate angularity, and flat or elongated coarse aggregate particles should be avoided Rounded fine aggregate particles are more desirable because of their positive effect on plastic concrete workability.

- Abrasion Resistance – the abrasion resistance of an aggregate is often used as a general index of its quality.
- Durability – resistance to freezing and thawing is necessary for concrete aggregates, and is related to the aggregate porosity, absorption, permeability, and pore structure.
- Deleterious Materials – aggregates should be free of potentially deleterious materials such as clay lumps, shales, or other friable particles, and other materials that could affect its chemical stability, weathering resistance, or volumetric stability.
- Particle Strength – for normal concrete pavements, aggregate strength is rarely tested. It is usually much greater than and therefore not as critical a parameter as the paste strength or the paste-aggregate bond. Particle strength is an important factor in high-strength concrete mixtures.

Table 24-5 provides a list of standard test methods that are used to assess the suitability of conventional mineral aggregates in Portland cement concrete paving applications.

Table 24-5. Concrete aggregate test procedures.

Property	Test Method	Reference
General Specifications	Concrete Aggregates	ASTM C33
	Ready Mixed Concrete	ASTM C94/ AASHTO M157
	Concrete Made by Volumetric Batching and Continuous Mixing	ASTM C685/ AASHTO M241
	Terminology Related to Concrete and Concrete Aggregates	ASTM C125
Gradation	Sizes of Aggregate for Road and Bridge Construction	ASTM D448/ AASHTO M43

Table 24-5. Concrete aggregate test procedures (continued).

Property	Test Method	Reference
Gradation (continued)	Sieve Analysis of Fine and Coarse Aggregate	ASTM C136/ AASHTO T27
Absorption	Specific Gravity and Absorption of Coarse Aggregate	ASTM C127/ AASHTO T85
	Specific Gravity and Absorption of Fine Aggregate	ASTM C128/ AASHTO T84
Particle Shape and Surface Texture	Flat and Elongated Particles in Coarse Aggregate	ASTM D4791
	Uncompacted Voids Content of Fine Aggregate (As Influenced by Particle Shape, Surface Texture, and Grading)	ASTM C1252/ AASHTO TP33
	Index of Aggregate Particle Shape and Texture	ASTM D3398
Abrasion Resistance	Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine	ASTM C535
	Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine	ASTM C131/ AASHTO T96
Durability	Aggregate Durability Index	ASTM D3744/ AASHTO T210
	Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate	ASTM C88/ AASHTO T104
	Soundness of Aggregates by Freezing and Thawing	AASHTO T103
Deleterious Components	Petrographic Examination of Aggregates for Concrete	ASTM C295
	Organic Impurities in Fine Aggregate for Concrete	ASTM C40
	Clay Lumps and Friable Particles in Aggregates	ASTM C142
	Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test	ASTM D2419
Volume Stability	Potential Volume Change of Cement-Aggregate Combinations	ASTM C342
	Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction	ASTM C227

Portland Cement and Supplementary Cementitious Materials

Although it comprises between only 7 to 15 percent of the absolute volume of concrete mixture, it is the hardened paste that is formed by hydration of the cement upon the addition of water that binds the aggregate particles together to form a stonelike mass. Hence, the properties of the concrete in the plastic and hardened state are greatly influenced by the properties of the cementing material, which can consist of Portland cement alone or blends of Portland cement with supplementary cementitious materials. Some of the more important properties of the cement binder include:

- Chemical Composition – differences in chemical composition, particularly with supplementary cementitious materials that could be less uniform than Portland cement, could affect early and ultimate strengths, heat released, setting time, and resistance to deleterious materials.

- Fineness – the fineness of the cement or supplementary cementitious materials affects heat release and rate of hydration. Finer materials react faster, with a corresponding increase in early strength development, primarily during the first 7 days. Fineness also influences workability, since the finer the material, the greater the surface area and frictional resistance of the plastic concrete.

- Soundness – refers to the ability of the cement paste to retain its volume after setting, and is related to the presence of excessive amounts of free lime or magnesia in the cement or supplementary cementitious material.

- Setting Time – the setting time for the cement paste is an indication of the rate at which hydration reactions are occurring and strength is developing and can be used as an indicator as to whether or not the paste is undergoing normal hydration reactions.

- False Set – false set or early stiffening of the cement paste is indicated by a significant loss of plasticity without the evolution of heat shortly after the concrete is mixed.

- Compressive Strength – compressive strength is influenced by cement composition and fineness. Compressive strengths for different cements or cement blends are established by compressive strength testing of mortar cubes prepared using a standard graded sand.

- Specific Gravity – specific gravity is not an indication of the quality of the cement, but is required for concrete mix design calculations. The specific gravity of Portland cement is approximately 3.15.

Table 24-6 provides a list of standard laboratory tests that are presently used to evaluate the mix design or expected performance of Portland cement and supplementary cementitious materials for use in concrete paving mixtures.

Table 24-6. Portland cement and supplementary cementitious materials test procedures.

Property	Test Method	Reference
General Specifications	Portland Cement	ASTM C150
	Blended Hydraulic Cement	ASTM C595
	Expansive Hydraulic Cement	ASTM C845
	Pozzolan Use as a Mineral Admixture	ASTM C618
	Ground Blast Furnace Slag Specifications	ASTM C989
	Silica Fume Specifications	ASTM C1240
Chemical Composition	Chemical Analysis of Hydraulic Cements	ASTM C114
Fineness	Fineness of Hydraulic Cement by the 150 μm (No. 100) and 75 μm (No. 200) Sieves	ASTM C184/ AASHTO T128
	Fineness of Hydraulic Cement and Raw Materials by the 300 μm (No. 50), 150 μm (No. 100) and 75 μm (No. 200) Sieves by Wet Methods	ASTM C786
	Fineness of Hydraulic Cement by the 45 μm (No. 325) Sieve	ASTM C430/ AASHTO T192
	Fineness of Portland Cement by Air Permeability Apparatus	ASTM C204/ AASHTO T153
	Fineness of Portland Cement by the Turbidimeter	ASTM C115/ AASHTO T98
Cement Soundness	Autoclave Expansion of Portland Cement	ASTM C151/ AASHTO T107
Setting Time	Time of Setting of Hydraulic Cement by Vicat Needle	ASTM C191/ AASHTO T131
	Time of Setting of Hydraulic Cement by Gillmore Needles	ASTM C266/ AASHTO T154
	Time of Setting of Hydraulic Cement Mortar by Modified Vicat Needle	ASTM C807

Table 24-6. Portland cement and supplementary cementitious materials test procedures (continued).

Property	Test Method	Reference
False Set	Early Stiffening of Portland Cement (Mortar Method)	ASTM C359/ AASHTO T185
	Early Stiffening of Portland Cement (Paste Method)	ASTM C451/ AASHTO T186
Compressive Strength	Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or 50-mm Cube Specimens)	ASTM C109/ AASHTO T106
	Compressive Strength of Hydraulic Cement Mortars (Using Portions of Prisms Broken in Flexure)	ASTM C349
Specific Gravity	Density of Hydraulic Cement	ASTM C188/ AASHTO T133

CONCRETE PAVING MATERIAL

The mix proportions for concrete paving mixtures are determined in the laboratory during mix design testing. This involves determination of the optimum characteristics of the mix in both the plastic and hardened states to ensure that the mix can be properly placed and consolidated, finished to the required texture and smoothness, and will have the desired properties necessary for pavement performance. Properly designed, placed, and cured concrete paving mixtures should be evaluated for the following properties:

Freshly Mixed (Plastic) Concrete

- Slump – slump is an indication of the relative consistency of the plastic concrete. Concrete of plastic consistency does not crumble but flows sluggishly without segregation.
- Workability – workability is a measure of the ease of placing, consolidating, and finishing freshly mixed concrete. Concrete should be workable but not segregate or bleed excessively.
- Setting Time – knowledge of the rate of reaction between cementing materials and water (hydration) is important to determine setting time and hardening. The setting times of

concrete mixtures do not correlate directly with the setting times of the cement paste because of water loss and temperature differences.

- Air Content – the amount of entrapped or entrained air in the plastic concrete can influence the workability of the concrete mixture and reduce its propensity for bleeding.

Hardened Concrete

- Strength – concrete pavements must have adequate flexural strength to support the design traffic loads (repetitions of loaded axles) that will be applied over the service life of the facility. While compressive strength can also be measured, flexural strength is more relevant to the design and performance of concrete pavements.

- Density – the density of concrete paving mixes varies depending on the amount and relative density of the aggregate, the amount of air that is entrained or entrapped, and the water and cementing materials content of the concrete.

- Durability – the hardened concrete pavement must be able to resist damage from freezing and thawing, wetting and drying, and chemical attack (e.g., from chlorides or sulfates in deicing salts).

- Air Content – the finished and cured concrete should have adequate entrained air in the hardened cement paste to be able to withstand cycles of freezing and thawing.

- Frictional Resistance – for user safety, the surface of an exposed concrete pavement must provide adequate frictional resistance and resist polishing under traffic. Frictional resistance is a function of the aggregates used and the compressive strength of the concrete.

- Volume Stability – concrete paving mixtures must be volumetrically stable and must not expand due to alkali aggregate reactivity. Concrete paving mixtures should not shrink excessively upon drying.

Table 24-7 provides a list of standard laboratory tests that are presently used to evaluate the mix design or expected performance of concrete paving mixtures.

Table 24-7. Concrete paving materials test procedures.

Property	Test Method	Reference
General Specifications	Ready Mixed Concrete	ASTM C94/ AASHTO M157
	Concrete Made by Volumetric Batching and Continuous Mixing	ASTM C685/ AASHTO M241
	Concrete Aggregates	ASTM C33
	Terminology Related to Concrete and Concrete Aggregates	ASTM C125
	Pozzolan Use as a Mineral Admixture	ASTM C618
	Ground Blast Furnace Slag Specifications	ASTM C989
	Chemical Admixtures for Concrete	ASTM C494
	Air Entraining Agents	ASTM C260
	Silica Fume Specifications	ASTM C1240
Slump	Slump of Hydraulic Cement Concrete	ASTM C143/ AASHTO T119
Workability	Bleeding of Concrete	ASTM C232/ AASHTO T158
Hydration and Setting	Time of Setting of Concrete Mixtures by Penetration Resistance	ASTM C403
Strength	Compressive Strength of Cylindrical Concrete Specimens	ASTM C39/ AASHTO T22
	Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)	ASTM C78/ AASHTO T96
	Splitting Tensile Strength of Cylindrical Concrete Specimens	ASTM C496/ AASHTO T198
Air Content	Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete	ASTM C457
	Air Content of Freshly Mixed Concrete by the Pressure Method	ASTM C231/ AASHTO T152
	Air Content of Freshly Mixed Concrete by the Volumetric Method	ASTM C173/ AASHTO T196
	Unit Weight, Yield, and Air Content of Concrete	ASTM C138

Table 24-7. Concrete paving materials test procedures (continued).

Property	Test Method	Reference
Density	Specific Gravity, Absorption, and Voids in Hardened Concrete	ASTM C642
Durability	Resistance of Concrete to Rapid Freezing and Thawing	ASTM C666
	Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals	ASTM C131/ AASHTO T96
Volume Stability	Length Change of Hardened Hydraulic-Cement Mortar and Concrete	ASTM C157
	Length Change of Concrete Due to Alkali-Carbonate Rock Reaction	ASTM C1105

REFERENCES FOR ADDITIONAL INFORMATION

ACI Manual of Concrete Practice, Part 1 - Materials and General Properties of Concrete. American Concrete Institute, Detroit, Michigan, 1994.

Kosmatka, S. H. and W. C. Panarese. *Design and Control of Concrete Mixtures.* Portland Cement Association, Skokie, Illinois, 1995.

Neville, A. M. *Properties of Concrete, Fourth Edition.* John Wiley & Sons, New York, New York, 1996.

INTRODUCTION

Aggregates are used in granular base and subbase layers below the driving surface layer(s) in both asphalt concrete and Portland cement concrete pavement structures. The aggregate base layers serve a variety of purposes, including reducing the stress applied to the subgrade layer and providing drainage for the pavement structure. The granular base layer is directly below the pavement surface and acts as the load bearing and strengthening component of the pavement structure. The granular subbase forms the lowest (bottom) layer of the pavement structure, and acts as the principal foundation for the subsequent road profile, provides drainage for the pavement structure, and protects the structure from frost.

Granular bases are typically constructed by spreading the materials in thin layers of 150 mm (6 in) to 200 mm (8 in) and compacting each layer by rolling over it with heavy compaction equipment.

MATERIALS

Aggregates used in granular base and subbase applications generally consist of sand and gravel, crushed stone or quarry rock, slag, or other hard, durable material of mineral origin. The gradation requirements vary with type (base or subbase).

Granular base materials typically contain a crushed stone content in excess of 50 percent of the coarse aggregate particles. Cubical particles are desirable, with a limited amount of flat or thin and elongated particles. The granular base is typically dense graded, with the amount of fines limited to promote drainage. Granular subbase is also dense graded, but tends to be somewhat more coarse than granular base. The requirement for crushed content for granular subbase is not required by many agencies, although provision of 100 percent crushed aggregates for base and subbase use is increasing in premium pavement structures to promote rutting resistance.

MATERIAL PROPERTIES AND TESTING METHODS

The granular base and subbase generally make up the greatest thickness of the pavement structure, and provide both bearing strength and drainage for the pavement structure. Hence, proper size, grading, shape, and durability are important attributes to the overall performance of the pavement structure. Granular base and subbase aggregates may consist of durable particles of crushed stone, gravel or slag capable of withstanding the effects of handling, spreading, and compacting without generation of deleterious fines.

Some of the more important properties of aggregates for granular base and subbase include:

- Gradation – a wide range of aggregate sizes and gradations are used depending on the pavement type and the conditions to which the granular base and subbase will be subjected. The aggregate grading markedly influences the base stability, drainage (permeability) and frost susceptibility. Aggregates for use as granular base tend to be dense-graded with a maximum size of 50 mm (2 in) or less, while granular subbase can have a nominal maximum size commonly up to 100 mm (4 in). The percentage of fines (minus 0.075 mm (No. 200 sieve)) in the granular base is limited, for drainage and frost-susceptibility purposes, to a maximum of 8 percent, with up to 12 percent permitted in granular subbase.

- Particle Shape – the use of angular, nearly equidimensional aggregate with rough surface texture is preferred over rounded, smooth aggregate particles. Thin or flat and elongated particles have reduced strength when load is applied to the flat side of the aggregate or across its shortest dimension and are also prone to segregation and breakdown during compaction, creating additional fines.

- Base Stability – granular base should have high stability, particularly in a flexible asphalt pavement structure. Large, angular aggregate, dense-graded and consisting of hard, durable particles, is preferred for stability. For maximum base stability, the granular base should have sufficient fines to just fill the voids and the entire gradation should be close to its maximum density. However, while base density is maximized at fines content between 6 and 20 percent, load-carrying capacity decreases when the fines content exceeds about 9 percent. Stability also increases with the percentage of crushed particles and increasing coarse aggregate size.

- Permeability – since the granular subbase provides drainage for the pavement structure, its grading and hydraulic conductivity are important. The fines content is usually limited to a maximum of 10 percent for normal pavement construction, and 6 percent where free-draining subbase is required.

- Plasticity – the presence of plastic fines can significantly reduce the load-carrying strength of the granular base and subbase.

- Abrasion Resistance – particles should have sufficient strength to resist degradation or breakdown during construction, under compaction or under traffic.

- Resilient Modulus – can assist in providing design coefficients for multi-layered pavements by defining the relationship between stress and the deformation of granular base and subbase layers.

Table 24-8 provides a list of standard test methods to assess the suitability of conventional materials for use in granular base applications.

Table 24-8. Granular aggregates test procedures.

Property	Test Method	Reference
General Specifications	Graded Aggregate Material for Bases or Subbases for Highways or Airports	ASTM D2940
Gradation	Sizes of Aggregate for Road and Bridge Construction	ASTM D448/ AASHTO M43
	Sieve Analysis of Fine and Coarse Aggregate	ASTM C136/ AASHTO T27
Particle Shape	Flat and Elongated Particles in Coarse Aggregate	ASTM D4791
	Uncompacted Voids Content of Fine Aggregate (As Influenced by Particle Shape, Surface Texture, and Grading	ASTM C1252/ AASHTO TP33
	Index of Aggregate Particle Shape and Texture	ASTM D3398
Base Stability	California Bearing Ratio	ASTM D1883/ AASHTO T193
	Moisture-Density Relations of Soils Using a 5.5 lb (2.5 kg) Rammer and a 12-in. (305 mm) Drop	ASTM D698/ AASHTO T99
	Moisture- Density Relations of Soils Using a 10-lb (4.54 kg) Rammer and an 18-in. (457 mm) Drop	AASHTO T180
Permeability	Permeability of Granular Soils (Constant Head)	ASTM D2434/ AASHTO T215
Plasticity	Determining the Plastic Limit and Plasticity Index of Soils	ASTM D4318/ AASHTO T90
	Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test	ASTM D2419/ AASHTO T176

Table 24-8. Granular aggregates test procedures (continued).

Property	Test Method	Reference
Abrasion Resistance	Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine	ASTM C535
	Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine	ASTM C131/ AASHTO T96
Resilient Modulus	Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils - SHRP Protocol P46	AASHTO T274

REFERENCES FOR ADDITIONAL INFORMATION

AASHTO Guide for the Design of Pavement Structures. American Association of State Highway and Transportation Officials, Washington, DC, 1993.

The Aggregates Handbook. National Stone Association (R. Barksdale, Editor), Washington, DC, 1991.

INTRODUCTION

An embankment refers to a volume of earthen material that is placed and compacted for the purpose of raising the grade of a roadway (or railway) above the level of the existing surrounding ground surface. A fill refers to a volume of earthen material that is placed and compacted for the purpose of filling in a hole or depression. Embankments or fills are constructed of materials that usually consist of soil, but may also include aggregate, rock, or crushed paving material.

Normally, the coarser fill materials are placed at or near the bottom or base of the embankment in order to provide a firm foundation for the embankment and also to facilitate drainage and prevent saturation. The top portion of an embankment usually is constructed of relatively high-quality, well-compacted subgrade material that is capable of supporting the overlying pavement layers and imposed wheel loadings without deflection or undesirable movement. The fill material used throughout the remainder of the embankment must be capable of meeting applicable specification quality requirements and be capable of being placed and compacted at or close to its maximum achievable density. The material is spread in relatively thin layers of 150 mm (6 in) to 200 mm (8 in) and each layer is compacted by rolling over it with heavy compaction equipment.

MATERIALS

Soils

Many different types of soils may be suitable for use in the construction of an embankment or fill, ranging from granular soils (sand and gravel), which are highly desirable, to the more finely sized soils (silt and clay), which are usually somewhat less desirable. Certain types of soils (such as saturated clays and highly organic soils) are considered unsuitable for use as materials in embankment or fill construction. Regardless of the type(s) of soil(s) used to construct embankments or fills, the material should be well graded, capable of being well compacted, be within a proper range of moisture to optimize compaction, and be free of unsuitable or deleterious materials, such as tree roots, branches, stumps, sludge, metal, or trash.

Oversize Materials

Some oversize materials (over 100 mm (4 in) in size), such as rocks, large stones, reclaimed paving materials, or air-cooled slags, can be used for the construction of embankment bases. Although the use of oversize materials can result in a stable embankment base, the oversize materials should have strong particles that do not readily break down under the action of construction machinery, but which have a range of sizes so that void spaces are at least partially filled.

MATERIAL PROPERTIES AND TESTING METHODS

Some of the more important properties of materials that are used for the construction of embankments or fills include:

- Gradation – well-graded fill materials that consist of two or more soil types, usually a mixture of granular and fine-grained soils, are most suitable for embankment construction. Because of the wide variety of soils that may be encountered, there is no universally recommended range of gradation for fill materials, although the maximum particle size should be less than 100 mm (4 in) so that it can be readily placed within a 200 mm (8 in) layer. Rock, or other oversize materials to be used as an embankment base, should consist of different size particles, with a specified maximum particle size.

- Unit Weight and Specific Gravity – fill materials can vary in unit weight over a fairly wide range, depending on the type of material and its moisture content. Fill materials that are relatively low in unit weight offer the advantage of transmitting less dead load to the underlying soil that supports an embankment. There are usually no specified requirements for a minimum or maximum unit weight, either before or after compaction.

- Moisture-Density Characteristics – the compaction characteristics (optimum moisture content and maximum dry density) of a soil fill material are the most important single property that affects embankment performance. Most specifications for embankment construction require the compacted fill material to have an in-place density that is within a certain percentage (usually 95 percent or greater) of the maximum dry density at a moisture content that is within a certain percentage (usually 3 percent or less) of optimum. The optimum moisture and maximum dry density of fill material(s) are determined in advance in the laboratory by means of either standard or modified moisture-density compaction tests. These tests methods are applicable for soils or earthen fill materials. Moisture-density characteristics cannot usually be determined for oversize (over 100 mm (4 in) materials) materials.

- Shear Strength – the shear strength characteristics (cohesion and/or internal friction) are indicative of the ability of a fill material to support loads that are imposed upon it under given drainage conditions. Shear strength characteristics are not always specified for earthen fill materials, but are determined by triaxial compression or direct shear testing and are used to compute the slope stability of an embankment.

- Compressibility – compressibility refers to the consolidation or settlement characteristics of a material under long-term loading conditions. The compressibility of a fill material is related to its shear strength, degree of compaction, void ratio, permeability, and degree of saturation. The settlement characteristics of an earthen fill material are determined by one-dimensional consolidation testing. Some settlement of an embankment or fill will occur during its construction, while the remainder of the settlement (if any) will occur in the postconstruction period.

- Bearing Capacity – bearing capacity refers to the ability of a fill material to support the loadings imposed upon it over the life of the facility without undue settlement, volume change, or structural damage. Bearing capacity can be determined by laboratory testing and by field load tests.

- Permeability – permeability or hydraulic conductivity refers to the ability of a soil (or an oversize material) to transmit water through the pore structure of the fill material at a given rate. This property is indicative of the ability of a compacted fill material to provide drainage for excessive moisture.

- Corrosion Resistance – corrosion is a basic chemical or electro-chemical property of a material that can induce damage to concrete structures, steel piles, or metal appurtenances with which the embankment or fill material may come in contact.

Table 24-9 provides a list of the standard test methods usually used to assess the suitability of conventional earthen fill materials for use in embankment or fill construction.

Table 24-9. Embankment or fill material test procedures.

Property	Test Method	Reference
Gradation	Particle Size Analysis of Soils	ASTM D422
	Sieve Analysis of Fine and Coarse Aggregate	ASTM D136
Unit Weight and Specific Gravity	Unit Weight and Voids in Aggregate	ASTM D29
	Specific Gravity of Soils	ASTM D854
	Relative Density of Cohesionless Soils	ASTM D2049
	Maximum Index Density of Soils Using a Vibratory Table	ASTM D4253
	Minimum Index Density of Soils and Calculation of Relative Density	ASTM D4254
Moisture-Density Characteristics	Moisture-Density Relations of Soils and Soil-Aggregate Mixtures Using 5.5 lb (2.49 kg) Rammer and 12 in. (305 mm) Drop	ASTM D698 (Standard)

Table 24-9. Embankment or fill material test procedures (continued).

Property	Test Method	Reference
Moisture-Density Characteristics (continued)	Moisture-Density Relations of Soils and Soil-Aggregate Mixtures Using 10 lb (4.54 kg) Rammer and 18 in. (457 mm) Drop	ASTM D1557 (Modified)
Compacted Density (In-Place Density)	Density of Soil in Place by the Sand-Cone Method	ASTM D1556
	Density and Unit Weight of Soil in Place by the Rubber Balloon Method	ASTM D2167
	Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow-Depth)	ASTM D2922
	Density of Soil in Place by the Sleeve Method	ASTM D4564
Shear Strength	Unconsolidated Undrained Compressive Strength of Cohesive Soils in Triaxial Compression	ASTM D2850
	Direct Shear Test of Soils Under Consolidated Drained Conditions	ASTM D3080
	Consolidated-Undrained Triaxial Compression Test on Cohesive Soils	ASTM D4767
Compressibility	One-Dimensional Consolidation Properties of Soils	ASTM D2435
	One-Dimensional Consolidation Properties of Soils Using Controlled-Strain Loading	ASTM D4186
	One-Dimensional Swell or Settlement Potential of Cohesive Soils	ASTM D4546
Bearing Capacity	California Bearing Ratio (CBR) of Laboratory-Compacted Soils	ASTM D1883
	Bearing Ratio of Soils in Place	ASTM D4429
Permeability	Permeability of Granular Soils by Constant Head	ASTM D2434
Corrosion Resistance	pH of Soil For Use in Corrosion Testing	ASTM G51
	Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method	ASTM G57
	Pore Water Extraction and Determination of the Soluble Salt Content of Soils by Refractometer	ASTM D4542

REFERENCES FOR ADDITIONAL INFORMATION

Nichols, Herbert L. *Moving the Earth.* McGraw-Hill Publishing Company, New York, New York, 1976.

U.S. Bureau of Reclamation. *Earth Manual.* Washington, DC, 1991.

INTRODUCTION

The term stabilized base, presented in this section, refers to a class of paving materials that are mixtures of one or more sources of aggregate and cementitious material(s) blended with a sufficient amount of water, that result in a mixture having a moist, nonplastic consistency that can be compacted to form a dense mass and gain strength. This class of base or subbase materials is not meant to include the stabilization of soils or aggregates using asphalt cement or emulsified asphalt.

Soil-cement (or cement-treated base) is probably the earliest example of a stabilized base material. Roller-compacted concrete, which is similar to, but more granular than soil-cement, is another type of stabilized base product. Probably the most frequently used type of stabilized base materials are the basic lime (and/or cement)-fly ash-aggregate family of mixtures, which can use many different combinations of reagents(s) and aggregate(s) together with coal fly ash. Calcium chloride has also been used to a lesser degree in some of the warmer regions of the country for mechanical stabilization of dense-graded aggregate base courses.

The purpose of a stabilized base or subbase layer is to provide a transitional load-bearing strata between the pavement layer, which directly receives the wheel loadings of vehicular traffic, and the underlying subgrade soil. Stabilized base or subbase materials may be used to provide support for either flexible or rigid pavements, but are more frequently used with flexible pavements.

Stabilized base or subbase materials are either mixed in place at the job site, or are mechanically combined in a mixing plant and transported to the site. These materials are spread evenly in loose layers on a prepared subgrade or subbase using either a blade-grader bulldozer, spreader box, or paving machine. Once the material has been spread, it is then densified by means of conventional rollers of compaction equipment.

MATERIALS

The components of a stabilized base or subbase mixture include aggregate, cementitious materials, and water.

Aggregates

Aggregates comprise the major portion of stabilized base. Normally, between 80 to 95 percent by weight of a stabilized base or subbase mix may consist of aggregates. A wide range of different types and gradations of aggregates have been used in stabilized base and subbase mixtures. These include conventional aggregate sources, such as crushed stone or sand and gravel, and other aggregate materials, such as blast furnace slag, recycled paving materials, and bottom ash or boiler slag from coal-fired power plants. Reclaimed pavement materials have also been successfully recycled into stabilized base and subbase mixtures, as have some marginal aggregates. Aggregates used should have the proper particle size, shape, gradation, and particle strength to contribute to a mechanically stable mixture.

Cementitious Materials

The key to strength development in stabilized base or subbase mixtures is in the matrix that binds the aggregate particles together. The strength of the matrix is affected by the cementitious material used in the mixture. The amount of cementitious material in a stabilized base or subbase mix usually ranges from 5 to 10 percent by weight of the mix, but may in some cases comprise as much as up to 20 percent by weight if a lighter weight aggregate is used.

A number of different cementitious materials have been successfully used to bind or solidify the aggregate particles in stabilized base or subbase mixtures. The material that has been most frequently used is Portland cement.

In some parts of the United States, mainly west of the Mississippi River, fly ash from the burning of sub-bituminous coal is widely available and, because it exhibits self-cementing characteristics when mixed with water, it can be used by itself with no other cementitious material to bind aggregate particles together.

Coal fly ash, produced during the combustion of bituminous coal, is frequently used in stabilized base mixtures. Since this type of fly ash is a pozzolan, the mixtures in which it is used are often referred to as pozzolanic stabilized base (PSB) mixtures. Pozzolans are materials composed of amorphous siliceous or siliceous and aluminous material in a finely divided (powdery) form (similar in size to Portland cement particles) that will, in the presence of water, react with an activator to form compounds possessing cementitious properties. Pozzolan activators are alkaline materials that contain calcium and magnesium compounds present in sufficient amounts to chemically react in the presence of water with the silicate and aluminates in the pozzolan. Descriptions of various kinds of pozzolans and their specifications are provided in ASTM C618.

In PSB compositions, the fly ash is usually used in combination with either lime, Portland cement, or kiln dust, plus water, to form the matrix that cements the aggregate particles together. When used with a chemical reagent, this type of fly ash normally comprises between 10 and 20 percent by weight of a stabilized base or subbase mix. When used with lighter weight aggregates (such as coal bottom ash), the percentage of fly ash may be as high as 30 percent or more.

MATERIAL PROPERTIES AND TESTING METHODS

Aggregates

Aggregates used in stabilized base and subbase mixtures play a major role in determining the quality and performance of stabilized base and subbase mixtures. Aggregate materials used in these types of mixtures must be properly graded and possess good to adequate particle shape, strength, and integrity.

AASHTO, in conjunction with the Association of General Contractors (AGC) and the American Road and Transportation Builders Association (ARTBA), has published a Guide Specification for Pozzolanic Stabilized Mixture (PSM) Base Course or Subbase (see reference section). This guide specification recommends quality requirements for aggregates.

The following is a list and brief comments on some of the more important properties of aggregates that are used in stabilized base and subbase mixes:

- Gradation – a wide range of aggregate sizes and gradations have been used in stabilized base and subbase mixtures. A number of different aggregate gradations may be considered, provided mixture design data for strength and durability can be furnished that indicates that such mixtures are capable of satisfying applicable strength and durability criteria. To maximize mix density, minimize void spaces, and not compromise the durability of the stabilized base mix, it has been recommended by the Portland Cement Association (PCA) and others that at least 55 percent of the aggregate used be finer than 4.75 mm (No. 4 sieve).

- Abrasion Resistance – aggregate particles in stabilized base and subbase mixtures must possess sufficient particle strength to resist degradation and breakdown during construction and under repeated traffic loadings.

- Durability – aggregates used in stabilized bases and subbases must be sound and durable and able to meet the soundness quality requirements.

- Unit Weight – the unit weight of the aggregate used in stabilized base and subbase mixtures is an indicator of the compacted density of the mix containing this aggregate.

- Deleterious Substances – aggregates used in stabilized base and subbase mixtures should be reasonably free of deleterious substances, such as clay, shale, coal, coke, vegetation, or other debris.

- Plasticity – the fraction of the aggregate that passes the No. 40 sieve should have a liquid limit no greater than 25 and a plasticity index less than 4 (essentially nonplastic).

Standard test methods typically used to assess the suitability of conventional aggregate materials for use in stabilized base and subbase applications are listed in Table 24-10.

Table 24-10. Stabilized base and subbase aggregate test procedures.

Property	Test Method	Reference
General Specifications	Materials for Aggregate and Soil-Aggregate Subbase, Base and Surface Courses	AASHTO M147
	Graded Aggregate Material for Bases or Subbases for Highways or Airports	ASTM D2940
Gradation	Sieve Analysis of Fine and Coarse Aggregates	ASTM C136/ AASHTO T27
	Sizes of Aggregate for Road and Bridge Construction	ASTM D448/ AASHTO M43
Particle Shape	Index of Aggregate Particle Shape and Texture	ASTM D3398
	Flat and Elongated Particles in Coarse Aggregate	ASTM D4791
Abrasion Resistance	Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine	ASTM C535
	Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine	ASTM C131/ AASHTO T96
Soundness	Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate	ASTM C88/ AASHTO T104
Unit Weight	Unit Weight and Voids in Aggregate	ASTM C29/C29M/ AASHTO T19
Deleterious Components	Sand Equivalent Value of Soils and Fine Aggregate (Indirect measure of clay content of aggregate mixes)	ASTM D2419
Liquid and Plastic Limit	Liquid Limit, Plastic Plasticity Index of Soils	ASTM D4318

Cementitious Materials

Cementitious materials used in stabilized base and subbase mixes must be capable of reacting to bind the particles of aggregate together into a stable mass that is able to support imposed wheel loadings and resist the deteriorating effects of climate and water. Some of the more important properties of cementitious materials used in a stabilized base application include:

- Fineness – the fineness of the cement or supplementary cementitious materials affects heat release and rate of hydration. Finer materials react faster, with a corresponding increase in early strength development. Fineness also influences workability, since the finer the material, the greater the surface area and frictional resistance of the plastic mixture.

- Setting Time – the setting time for the cement paste is an indication of the rate at which hydration reactions are occurring and strength is developing.

- Compressive Strength – compressive strength is influenced by cement composition and fineness. Compressive strengths for different cements or cement blends are established by compressive strength testing of mortar cubes.

- Specific Gravity – specific gravity is not an indication of the quality of the cement, but is required for concrete mix design calculations.

Table 24-11 provides a list of standard laboratory tests that are presently used to evaluate the mix design or expected performance of cementitious materials for use in stabilized base mixtures.

Table 24-11. Cementitious materials test procedures.

Property	Test Method	Reference
General Specifications	Portland Cement	ASTM C150
	Blended Hydraulic Cement	ASTM C595
	Expansive Hydraulic Cement	ASTM C845
	Pozzolan Use as a Mineral Admixture	ASTM C618
Fineness	Fineness of Hydraulic Cement by the 150 μm (No. 100) and 75 μm (No. 200) Sieves	ASTM C184/ AASHTO T128
	Fineness of Hydraulic Cement and Raw Materials by the 300 μm (No. 50), 150 μm (No. 100) and 75 μm (No. 200) Sieves by Wet Methods	ASTM C786

Table 24-11. Cementitious materials test procedures (continued).

Property	Test Method	Reference
Fineness (continued)	Fineness of Hydraulic Cement by the 45 µm (No. 325) Sieve	ASTM C430/ AASHTO T192
	Fineness of Portland Cement by Air Permeability Apparatus	ASTM C204/ AASHTO T153
	Fineness of Portland Cement by the Turbidimeter	ASTM C115/ AASHTO T98
Setting Time	Time of Setting of Hydraulic Cement by Vicat Needle	ASTM C191/ AASHTO T131
	Time of Setting of Hydraulic Cement by Gillmore Needles	ASTM C266/ AASHTO T154
	Time of Setting of Hydraulic Cement Mortar by Modified Vicat Needle	ASTM C807
Compressive Strength	Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or 50 mm Cube Specimens)	ASTM C109/ AASHTO T106
	Compressive Strength of Hydraulic Cement Mortars (Using Portions of Prisms Broken in Flexure)	ASTM C349
Specific Gravity	Density of Hydraulic Cement	ASTM C188/ AASHTO T133

The most important properties of fly ash (or other pozzolans) used in stabilized base mixtures include:

- Fineness – the fly ash particles must be fine enough to provide sufficient surface area and for reaction with Portland cement or other activators (such as lime, lime kiln dust, or cement kiln dust) and to enhance the flowability of the flowable fill mix.
- Pozzolanic Activity – pozzolanic fly ash must be composed of a sufficient amount of silica and alumina to react chemically with available calcium to form cementitious compounds, while self-cementing fly ash must contain sufficient calcium and magnesium silicate and aluminates to develop strength in the presence of water.

Table 24-12 lists applicable test methods that contain criteria for evaluating the suitability of fly ash for use in stabilized base and subbase mixtures.

Table 24-12. Pozzolan test procedures.

Property	Test Method	Reference
General Specification	Fly Ash and Other Pozzolans for Use with Lime	ASTM C593
Fineness	Sampling and Testing Fly Ash or Natural Pozzolans for Use as Mineral Admixture in Portland Cement Concrete	ASTM C311
Pozzolanic Activity	Characterization of Fly Ash for Use in Soil Stabilization	ASTM C311

STABILIZED BASE OR SUBBASE MIXTURES

The mix proportions for a properly designed stabilized base or subbase mixture are determined in the laboratory during mix design testing. To perform properly in the field, a well-designed stabilized base or subbase mixture must be properly compacted and be capable of developing sufficient strength and durability to meet or exceed design criteria. Properly designed stabilized base or subbase materials should be evaluated for the following properties:

- Compressive Strength – this refers to the ability of a well-compacted stabilized base mixture to develop a specified minimum level of unconfined compressive strength under specified curing conditions.

- Durability – this refers to the ability of a well-compacted stabilized base mixture to resist the deteriorating effects of cyclic freezing and thawing, and/or wetting and drying, once the material has achieved its design strength.

- Maximum Dry Density – the maximum density or compacted unit weight of a stabilized base mixture that has been compacted at or very close to optimum moisture content using prescribed laboratory compaction procedures.

- Optimum Moisture – the moisture content at which the maximum dry density of a stabilized base mixture is achieved in the laboratory using prescribed compaction procedures.

- Compacted Density – the actual in-place density of a stabilized base material that has been compacted in the field according to project specifications.

- Volumetric Stability – this refers to the ability of a well-compacted stabilized base material to maintain its volumetric dimensions and resist potentially expansive chemical reactions after placement and compaction.

- Resilient Modulus – this property defines the relationship between repeated axial stress applied to a base or subbase material and the deformation response of the material and can be used in multi layered pavement design.

Table 24-13 provides a list of standard laboratory test methods that are used to evaluate the mix design properties and/or performance characteristics of stabilized base or subbase mixtures.

Table 24-13. Stabilized base and subbase material test procedures.

Property	Test Method	Reference
Compressive Strength	Fly Ash and Other Pozzolans for use with Lime	ASTM C593
	Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory	ASTM D1632
Freeze-Thaw Durability	Fly Ash and Other Pozzolans for use with Lime	ASTM C593
	Freezing and Thawing Tests of Compacted Soil-Cement Mixtures	ASTM D560
Maximum Dry Density and Optimum Moisture Content	Moisture-Density Relations of Soils and Soil-Aggregate Mixtures using 5.5 lb (2.49 kg) Rammer and 12 in (305 mm) Drop or Moisture-Density Relations of Soils and Soil-Aggregate Mixtures using 10 lb (4.59 kg) Rammer and 18 in (457 mm) Drop	ASTM D698 (Standard) or ASTM D1557 (Modified)
Compacted Density	Density of Soil in Place by the Sand Cone Method	ASTM D1556
	Density and Unit Weight of Soil in Place by the Rubber Balloon Method	ASTM D2167
Volumetric Stability	One-Dimensional Expansion, Shrinkage, and Uplift Pressure of Soil-Lime Mixtures	ASTM D3877
Resilient Modulus	Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils	AASHTO T274

REFERENCES FOR ADDITIONAL INFORMATION

AASHTO/AGC/ARTBA Guide Specification for Pozzolanic Stabilized Mixture (PSM) Base Course or Subbase. American Association of State Highway and Transportation Officials, Washington, DC, 1988.

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Materials for Stabilization. American Road and Transportation Builders Association, Washington, DC, 1977.

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INTRODUCTION

Flowable fill refers to a cementitious slurry consisting of a mixture of fine aggregate or filler, water, and cementitious material(s), which is used primarily as a backfill in lieu of compacted earth. This mixture is capable of filling all voids in irregular excavations and hard to reach places (such as under and around pipes), is self-leveling, and hardens in a matter of a few hours without the need for compaction in layers. Flowable fill is sometimes referred to as controlled density fill (CDF), controlled low strength material (CLSM), lean concrete slurry, and unshrinkable fill.

Flowable fill is defined by the American Concrete Institute (ACI) as a self-compacting cementitious material that is in a flowable state at placement and has a compressive strength of 8.3 MPa (1,200 lb/in^2) or less at 28 days. Most current applications for flowable fill involve unconfined compressive strengths of 2.1 MPa (300 lb/in^3) or less.

Flowable fill materials are primarily used in below grade applications such as utility trenches, where low strength and ease of placement are required. Flowable fill is typically placed using conventional ready-mix concrete trucks. In many cases, these materials are designed so that they are comparable in strength to the surrounding soil after hardening, making excavation at a later time possible.

MATERIALS

Fine aggregates or fillers (usually sand) are often used in flowable fill mixtures that are produced at ready-mix plants, especially higher strength CLSM mixtures. Portland cement and/or supplementary cementitious materials and water are essential ingredients in all flowable fill mixtures, since it is the hydration of these cementitious materials that enables the flowable fill mixture to harden and develop strength.

Fine Aggregate or Filler

Fine aggregate or filler material provides the solids to develop compressive strength, as well as load-carrying capability. For purposes of this discussion, fine aggregates are materials with particles in a size range of 4.75 mm (No. 4 sieve) to 0.075 mm (No. 200 sieve), and filler refers to those materials with a size range of less than 0.075 mm (No. 200 sieve). The properties of fine aggregate or filler material that are most relevant to its use in flowable fill are its gradation and unit weight. The composite material must be sufficiently finely graded to enhance the flowability of the mix, but may also be granular enough to be able to drain some of the excess water from the mix prior to initial hardening.

Sand is the most commonly used flowable fill material, although other materials (such as coal bottom ash, fly ash, spent foundry sand, quarry fines, and baghouse dust) have also been used. Depending on the unit weight of the flowable fill material, a cubic yard of flowable fill may contain between 680 and 1400 kg (1500 and 3000 pounds) of fine aggregate or filler material.

Cementitious Materials

It is possible to use a variety of cementitious materials to produce a suitable cementitious slurry with desirable compressive strength and flow properties. These materials can be divided into three general categories. They include Portland cement, pozzolanic materials, and self-cementing materials.

Portland cements are hydraulic cements that set and harden by reacting with water, through hydration, to form a solidified mass. The amount of Portland cement in a flowable fill mix, together with the water and the quantity of Portland cement added, determines the ultimate strength of the mixture. At lower cement contents (in the 3 to 5 percent by weight range), the 28-day unconfined compressive strength of a flowable fill mixture is typically in the 0.5 to 1.0 MPa (75 to 150 lb/in^2) range.

Pozzolanic materials are materials composed of amorphous siliceous or siliceous and aluminous material in a finely divided (powdery) form (similar in size to Portland cement particles) that will, in the presence of water, react with an activator (typically calcium hydroxide and alkalis) to form compounds possessing cementitious properties. Descriptions of various kinds of pozzolans and their specifications are provided in ASTM C618. Self-cementing materials are materials that react with water to form hydration products without any activator.

Coal fly ash is frequently used in flowable fill mixtures as a cementitious material and because its fine, spherical shaped particles greatly improve the fluidity or flowability of the mix. Fly ash generated during the combustion of bituminous coals exhibits pozzolanic properties and reacts with calcium oxide to form a cement paste. Fly ash generated during subbituminous coal combustion exhibits self-cementing properties and is sometimes used instead of Portland cement in areas where it is readily available.

Water

The amount of water in a flowable fill mix has a direct effect on the flowability and strength development of the mixture. Sufficient water must be added to lubricate the solids in the mixture in order to achieve the desired degree of flowability, which is frequently related to the slump of the mix. At a given cement content, an increase in the water content usually results in a slight decrease in the compressive strength development of the mix over time. Water requirements for mixture fluidity depend on the surface properties of the solids in the mixture. A range of 250 to

400 liters per cubic meter (50 to 80 gallons per cubic yard) will satisfy most material combinations.

MATERIAL PROPERTIES AND TESTING METHODS

Fine Aggregate or Filler

Proper size and grading are needed for a fine aggregate or filler material to effectively contribute to the flowability of a flowable fill mixture. The most commonly used filled materials are sand and coal fly ash (pozzolanic), with the choice of material usually decided by availability and comparative cost. The unit weight or specific gravity of the fine aggregate or filler material determines to a great extent the unit weight or specific gravity of the resultant flowable fill. The following is a listing and brief comments on some of the more important properties of fine aggregate or filler material used in flowable fill mixtures.

- Gradation – the fine aggregate or filler particles must be finely graded to prevent a harsh mix (a stiff, low flow mix usually resulting from a preponderance of granular material) and have a sufficient range of finer size particles to provide flowability, stability, and minimal void spaces in the flowable fill mix.

- Unit Weight – the fine aggregate or filler materials should be within a relatively low to moderate range of unit weight in order to encourage flowability and discourage segregation of particles in the resultant flowable fill mix.

Table 24-14 lists standard test methods used to evaluate fine aggregate or filler materials for use in flowable fill.

Table 24-14. Fine aggregate or filler material test procedures.

Property	Test Method	Reference
Gradation	Particle Size Analysis of Soils	ASTM D422
Unit Weight	Unit Weight and Voids in Aggregate	ASTM D29
	Specific Gravity of Soils	ASTM D854

Cementitious Materials

The type of cementitious materials used in the flowable fill mix design will play a major role in determining the final compressive strength and flowability of the mix. Some of the more important properties of cementitious materials used in a flowable fill mix include:

- Fineness – the fineness of the cement or supplementary cementitious materials affects heat release and rate of hydration. Finer materials react faster, with a corresponding ncrease in early strength development. Fineness also influences workability, since the finer the material, the greater the surface area and frictional resistance of the plastic concrete.
- Setting Time – the setting time for the cement paste is an indication of the rate at which hydration reactions are occurring and strength is developing.
- Compressive Strength – compressive strength is influenced by cement composition and fineness. Compressive strengths for different cements or cement blends are established by compressive strength testing of mortar cubes.
- Specific Gravity – specific gravity is not an indication of the quality of the cement, but is required for concrete mix design calculations. The specific gravity of Portland cement is approximately 3.15.

Table 24-15 provides a list of standard laboratory tests that are presently used to evaluate the mix design or expected performance of cementitious materials for use in flowable fill mixtures.

Table 24-15. Cementitious materials test procedures.

Property	Test Method	Reference
General Specifications	Portland Cement	ASTM C150
	Blended Hydraulic Cement	ASTM C595
	Expansive Hydraulic Cement	ASTM C845
	Pozzolan Use as a Mineral Admixture	ASTM C618
Fineness	Fineness of Hydraulic Cement by the 150 µm (No. 100) and 75 µm (No. 200) Sieves	ASTM C184/ AASHTO T128
	Fineness of Hydraulic Cement and Raw Materials by the 300 µm (No. 50), 150 µm (No. 100) and 75 µm (No. 200) Sieves by Wet Methods	ASTM C786

Table 24-15. Cementitious materials test procedures (continued).

Property	Test Method	Reference
Fineness (continued)	Fineness of Hydraulic Cement by the 45 µm (No. 325) Sieve	ASTM C430/ AASHTO T192
	Fineness of Portland Cement by Air Permeability Apparatus	ASTM C204/ AASHTO T153
	Fineness of Portland Cement by the Turbidimeter	ASTM C115/ AASHTO T98
Setting Time	Time of Setting of Hydraulic Cement by Vicat Needle	ASTM C191/ AASHTO T131
	Time of Setting of Hydraulic Cement by Gillmore Needles	ASTM C266/ AASHTO T154
	Time of Setting of Hydraulic Cement Mortar by Modified Vicat Needle	ASTM C807
Compressive Strength	Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or 50 mm Cube Specimens)	ASTM C109/ AASHTO T106
	Compressive Strength of Hydraulic Cement Mortars (Using Portions of Prisms Broken in Flexure)	ASTM C349
Specific Gravity	Density of Hydraulic Cement	ASTM C188/ AASHTO T133

As noted previously, coal fly ash can be used in several ways in flowable fill, depending on the type of fly ash and the amount that is used. Pozzolanic fly ash, when used in relatively small quantities (15 percent or less by weight of total mix) can enhance strength development and improve the flowability of the mix. When used in large quantities (up to 94 percent by weight of total mix), pozzolanic fly ash also acts as the filler in the mix. Self-cementing fly ash can be used in relatively small quantities (15 percent or less by weight of total mix) to increase strength development or reduce hardening time in combination with Portland cement, or to simply function as a substitute or complete replacement for Portland cement. In either case, the most important properties of fly ash (or other pozzolans) used in flowable fill mixes include:

- Fineness – the fly ash particles must be fine enough to provide sufficient surface area and for reaction with Portland cement or other activators (such as lime, lime kiln dust, or cement kiln dust) and to enhance the flowability of the flowable fill mix.

- Pozzolanic Activity – pozzolanic fly ash must be composed of a sufficient amount of silica and alumina to react chemically with available calcium to form cementitious compounds, while self-cementing fly ash must contain sufficient calcium and magnesium silicate and aluminates to develop strength in the presence of water.

Table 24-16 lists standard test methods used to evaluate pozzolans, including coal fly ash, for its suitability in flowable fill applications.

Table 24-16. Pozzolan test procedures.

Property	Test Method	Reference
Fineness	Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete	ASTM C311
Pozzolanic Activity	Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete	ASTM C618

FLOWABLE FILL MIXTURE

Flowable fill mixtures possess the characteristics of a high-quality compacted earth backfill after hardening, while resembling a very workable, lean concrete mix when produced, transported, and placed. The most important physical characteristics of flowable fill mixtures are its strength development, flowability, hardening time, bleeding and shrinkage, unit weight, bearing capacity, shear strength, and corrosion resistance.

- Strength Development – the most important property of flowable fill is its strength, measured as unconfined compressive strength. Strength development in flowable fill mixtures is directly related to the components of the mix.

- Flowability – flowability in the placement of flowable fill mixtures is primarily a function of the water content, although fly ash improves the flowability in the same way that fly ash makes concrete more pumpable. The higher the water content, the more flowable the mix. Flowability can be measured by one of several different methods, including slump and flow cone tests. The normal slump range for flowable fill mixtures is 150 to 250 mm (6 to 10 in). This range of slump corresponds to a flow time of 30 to 60 seconds through a standard flow cone.

- Hardening Time – the hardening time of flowable fill mixtures is directly related to the cement type, its content, the filler content (including fly ash), as well as the water content and weather conditions. Hardening of flowable fill mixes containing 5 percent cement (that is sufficient to support the weight of an average person) can usually be expected in about 1 to 4 hours. Within 24 hours, construction equipment is usually able to move across the surface of the flowable fill without any apparent damage.

- Bleeding and Shrinkage – some bleeding and shrinkage is possible in flowable fill mixes with relatively high water contents. Evaporation of bleed water from such mixes often results in a shrinkage of the flowable fill. The shrinkage may occur laterally as well as vertically, and may manifest itself as shrinkage cracks in the top surface of the material. No shrinkage or settlement is expected in flowable fill mixes once initial hardening has occurred. The main concern with shrinkage cracking is most likely to be the potential for water infiltration, freezing, and subsequent frost damage.

- Unit Weight – the density or unit weight of flowable fill mixtures is dependent primarily on the unit weight of the filler or aggregate material. The unit weight of mixtures with high sand filler content is normally in the range of 1900 to 2350 kg/m^3 (115 to 145 lb/ft^3). The unit weight of flowable fill mixtures in which fly ash is used as the filler material is normally in the range of 1500 to 1900 kg/m^3 (90 to 115 lb/ft^3). Where poor soil bearing conditions require the use of a lightweight fill material, low-density CLSM mixtures can be produced by the introduction of a preformed foaming agent, with higher dosages resulting in a greater reduction in mix density. The unit weight of low density CLSM mixtures can range from 320 to 1300 kg/m^3 (20 to 80 lb/ft^3), depending on the amount of preformed foam that is injected into the mixture during batching.

- Bearing Strength – the bearing strength of flowable fill mixtures is directly related to their unconfined compressive strength. A flowable fill mixture with a 28-day unconfined compressive strength of 1.0 MPa (150 lb/in^2) has a bearing strength of approximately 9000 kg/m^2 (10 tons/ft^2). This is roughly three times greater than the bearing strength of a high quality, well-compacted granular borrow soil As the unconfined compressive strength of the mixture increases over time, so does the bearing strength.

- Shear Strength – triaxial shear strength testing of flowable fill mixes has shown internal friction angles ranging from 20 degrees for mixes using fine sand to 30 degrees for mixes using concrete sand. The cohesion of hardened flowable fill mixes has been found to be approximately 30 percent of the unconfined compressive strength.

- Corrosion Resistance – contact between flowable fill and metal pipes or concrete should be avoided so as not to promote corrosion of these materials. Corrosion is usually associated with acidity (low pH) and low electrical resistivity, although the solubility of constituents such as sulfates also affects corrosion. Flowable fill is ordinarily slightly alkaline and its resistivity increases as the material hardens and the cement continues to hydrate, so that within a few days, flowable fill usually has an electrical resistivity that is sufficient to alleviate most corrosivity concerns.

A list of the standard test methods usually used to evaluate flowable fill materials is given in Table 24-17.

Table 24-17. Flowable fill test procedures.

Property	Test Method	Reference
Strength Development	Unconfined Compressive Strength of Cohesive Soil	ASTM D2166
	Unconfined Compressive Strength Index of Chemical-Grouted Soils	ASTM D4219
Flowability	Slump of Portland Cement Concrete	ASTM C143
	Flow of Grout for Preplaced-Aggregate (Flow Cone Method)	ASTM C939
Hardening Time	Time of Setting of Concrete Mixtures by Penetration Resistance	ASTM C403
Bleeding and Shrinkage	Change in Height at Early Ages of Cylindrical Specimens from Cementitious Mixtures	ASTM C827
Unit Weight	Unit Weight, Yield, and Air Content of Concrete	ASTM C138
Bearing Strength	California Bearing Ratio (CBR) of Laboratory-Compactive Soils	ASTM D1883
Shear Strength	Unconsolidated Undrained Compressive Strength of Cohesive Soils in Triaxial Compression	ASTM D2850
	Direct Shear Test of Soils Under Consolidated Drained Conditions	ASTM D3080
Corrosion Resistance	pH of Soil for Use in Corrosion Testing	ASTM G51
	Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method	ASTM G57
	Optimum SO_3 in Portland Cement	ASTM C563

REFERENCES FOR ADDITIONAL INFORMATION

American Concrete Institute. *Controlled Low Strength Materials (CLSM)*. Report No. 229R-94, ACI Committee 229, Detroit, Michigan, July, 1994.

Portland Cement Association. *Cementitious Grouts and Grouting*. Skokie, Illinois, 1990.