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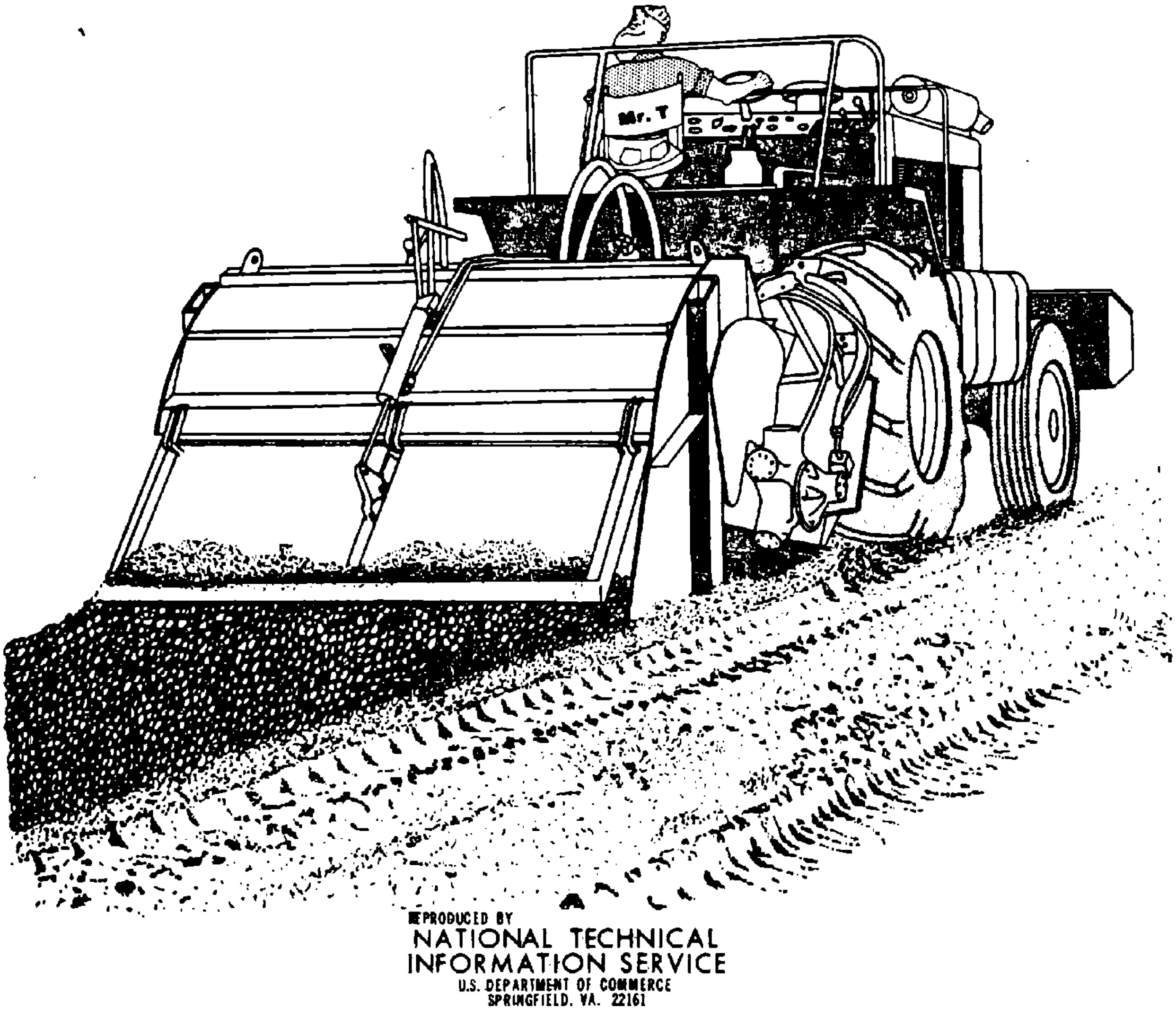
SOIL STABILIZATION IN PAVEMENT STRUCTURES
A USER'S MANUAL

VOLUME 1
PAVEMENT DESIGN AND CONSTRUCTION CONSIDERATIONS



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SOIL STABILIZATION IN PAVEMENT STRUCTURES

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VOLUME 1

PAVEMENT DESIGN AND CONSTRUCTION CONSIDERATIONS

Ronald L. Terrel, Jon A. Epps, Ernest J. Barenberg,
James K. Mitchell, Marshall R. Thompson

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by

TERREL, EPPS, and ASSOCIATES
6846 52nd Avenue N.E.
Seattle, Washington 98115

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FOREWORD

The primary purpose of this manual is to provide background information for those engineers responsible for utilizing soil stabilization as an integral part of a pavement structure. Information is included which will allow the pavement design engineer to determine the thickness of stabilized layer(s) for a pavement in a specific climate and subjected to definable highway traffic. The construction engineer will find information on quality control, specifications and construction sequences. The materials engineer has been provided with information that will allow the determination of the type and amount of stabilizers that are suitable for a particular soil.

The manual has not been written to endorse one type of a chemical stabilizer over another. Nor is it intended to provide the specific features of one manufacturer's products. Rather, it explains the general characteristics of chemical soil stabilization and offers a method for evaluating the benefits of chemical stabilization versus the conventional mechanical stabilization operations.

A thorough study of the manual should enable the engineer to recommend where, when and how soil stabilization should be used. It may also act as an aid in solving problems that may arise on soil stabilization projects.

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I. INTRODUCTION

PURPOSE AND SCOPE

Purpose

This two volume user's manual was developed to provide guidance for pavement design, construction and materials engineers responsible for soil stabilizations operations associated with transportation systems. Volume I of the manual (Pavement Design and Construction Considerations) follows and has been prepared for pavement design and construction engineers. This volume describes a method for selection of the type of stabilizers as well as pavement thickness design methods and construction information. Quality Control, guide specifications, cost and energy considerations are contained in the Appendices. Volume 2 of the manual (Mixture Design Considerations) has been prepared for materials engineers. This volume describes methods for selection of the type and amount of stabilizers. Methods of estimating stabilizer contents are presented as well as detailed test methods, mixture design criteria and typical mixture criteria.

The manual is directed to the engineer who is reasonably familiar with pavement technology, but who has limited experience with stabilized soil construction. Current technology of soil stabilization is presented in a complete but concise format such that the engineer can grasp the key elements and apply the information to his own needs. Suggested additional references are provided so that the reader may follow up on details of interest that are beyond the scope of this manual.

The information in this manual was obtained from an extensive review of published literature from the United States and abroad. In addition, the authors' familiarization and experience, coupled with correspondence and project site visits, have provided a background from which to extract pertinent information of direct use to the design and construction engineer. In short, it is presented as a state-of-the-practice of soil stabilization for pavements.

Every attempt has been made to present information that is technically correct and that can be applied with reasonable confidence. The methodology is provided with regard to acceptable testing methods that are generally known in the field and these are suitably referenced. Where newer or less known techniques or other information may not be readily available, it is provided in the manual. However, it will be necessary for the engineer to take into consideration local economic factors, climatic conditions, and other local aspects of a project in order to make prudent decisions as to designs and application of the technology contained herein.

Scope

This volume will provide the engineer with information to perform the following:

1. Develop alternative pavement designs which contain both unstabilized and stabilized layers (Chapter III),
2. Compare life cycle costs of alternate pavement designs (Appendix C),
3. Compare energy requirements of alternative pavement designs (Appendix D),
4. Identify construction sequences and methods suitable for soil stabilization operations (Chapter IV and Appendix B),
5. Identify construction equipment suitable for soil stabilization operations (Chapter IV and Appendix B),
6. Prepare specifications for soil stabilization operations (Appendix B), and
7. Prepare quality control methods for soil stabilization operations (Appendix A).

Stabilization as used in this manual refers to the use of the following chemicals for base and subbase stabilization:

1. Lime,
2. Lime-fly ash,
3. Portland cement,
4. Asphalt, and
5. Combinations of the above.

The use of other chemical stabilizers is not discussed. Mechanical stabilization is not considered in detail; however, certain comparisons can be made between mechanical and chemical stabilization by use of this manual.

BACKGROUND

The concept of soil improvement or modification through stabilization with additives has been around for several thousand years. At least as early as 5000 years ago, soil was stabilized with lime or pozzolans. Although this process of improving the engineering properties of soils has been practiced for centuries, soil stabilization did not gain significant acceptance for road and airfield construction in the U.S. until after World War II. Today, stabilization with lime, lime-fly ash, portland cement, and bituminous materials is popular in only some areas of the country.

One of the major concerns in recent years has been shortage of conventional aggregates. The highway construction industry consumes over half of the annual production of aggregates (1). However, this traditional use of aggregates in pavement construction has resulted in acute shortages in those areas that normally have adequate supplies. Other areas of the country have never had good quality aggregates available locally. Metropolitan areas have also experienced shortages. The reasons include lack of the raw materials, environmental and zoning regulations which prohibit mining and production of aggregates, and land use patterns which make aggregate deposits inaccessible. These factors, and others, combine to produce an escalation of aggregate costs, with a resultant increase in highway construction and maintenance costs. Consequently, there is a great need to find more economical replacements for conventional aggregates. A natural result is that attention be focused on substitute materials such as stabilized soils and marginal aggregates that can be upgraded through stabilization.

Another area of concern has been the energy crisis brought on by the temporary shortage of petroleum experienced in the early and late 1970's. It is rapidly becoming a practice to consider the energy demands of a project as well as cost. In terms of highway construction materials, the trend will be toward the use of materials which require less energy input in their production, handling, and placement. A recent study (2) revealed that the energy requirements for producing the materials for various asphalts, crushed stone, and portland cement concrete pavements ranged from 30 to 96 percent of the total energy required for production, handling, and placing of various pavements. Since relatively small quantities of binders such as lime, cement, fly ash, and asphalt can be used to improve pavement layers using stabilization technology, total energy demands may be reduced as well as costs.

In summary, existing literature suggests that soil stabilization is a desired design alternative. Specifically, soil stabilization may provide the following engineering advantages as compared to conventional unstabilized construction materials:

1. Function as a working platform (construction expediency),

2. Reduce dusting,
3. Water-proof the soil,
4. Upgrade marginal materials,
5. Improve strength,
6. Improve durability,
7. Control volume change of soils,
8. Improve workability of soil,
9. Drying of wet soils,
10. Reduce pavement thickness requirements,
11. Conserve aggregate materials,
12. Reduce cost,
13. Conserve energy, and
14. Provide a temporary or permanent wearing surface.

DEFINITIONS

Discussion of soil and aggregate stabilization requires use of terminology that may not be familiar, or at least needs to be defined for clarification. The following terms are presented with brief definitions as used in the manual.

General Definitions

Soil (Earth) - Sediments or other unconsolidated accumulations of solid particles produced by the physical and chemical disintegration of rocks, and which may or may not contain organic matter (ASTM D-18) (3).

Soil Stabilization - Chemical or mechanical treatment designed to increase or maintain the stability of a mass of soil or otherwise to improve its engineering properties (ASTM D-18).

Chemical Stabilization - The altering of soil properties by use of certain chemical additives which when mixed into a soil often change the surface molecular properties of the soil grains and, in some cases, cement the grains together resulting in strength increases.

Mechanical Stabilization - The alteration of soil properties by changing the gradation of the soil by the addition or removal of particles or by densifying or compacting the soil.

Aggregate - A granular material of mineral composition such as sand, gravel, shell, slag, or crushed stone, used with a cementing medium to form mortars or cement, or alone as in base courses, railroad ballasts, etc.

AASHO - An abbreviation used to designate the American Association of State Highway Officials. The name of the group was recently changed to the American Association of State Highway and Transportation Officials, and the current abbreviation AASHTO is also used.

ASTM - An abbreviation used to designate the American Society for Testing and Materials.

Definitions Associated with Lime Stabilization

Lime - All classes of quicklime and hydrated lime, both calcitic (high calcium) and holomitic (ASTM C593).

Definitions Associated with Lime-Fly Ash Stabilization

LFA - An abbreviation used to designate a mixture of lime-fly ash-aggregates.

LCFA - An abbreviation used to designate a mixture of lime- and cement-fly ash aggregates.

LFS - An abbreviation used to designate a mixture of lime-fly ash and soil.

Definitions Associated with Portland Cement Stabilization

Portland Cement - A hydraulic cement produced by pulverizing clinker consisting essentially of hydraulic calcium silicates, and usually containing one or more of the forms of calcium sulfate as an interground addition (ASTM C-1). Portland cement will be referred to as cement in this manual.

Cement Stabilized Soil - A mixture of soil and measured amounts of portland cement and water which is thoroughly mixed, compacted to a high density and protected against moisture loss during a specific curing period.

Soil-Cement - A hardened material formed by curing a mechanically compacted intimate mixture of pulverized soil, portland cement and water. Soil-cement contains sufficient cement to pass specified durability tests.

Cement-Modified Soil - An unhardened or semi-hardened intimate mixture of pulverized soil, portland cement, and water. Significantly smaller cement contents are used in cement-modified soil than in soil-cement.

Plastic Soil-Cement - A hardened material formed by curing an intimate mixture of pulverized soil, portland cement, and enough water to produce a mortarlike consistency at the time of mixing and placing. Plastic soil-cement can be used for highway ditch linings.

Definitions Associated with Asphalt Stabilization

Bitumen - A class of black or dark-colored (solid, semisolid, or viscous) cementitious substances, natural or manufactured, composed principally of high molecular weight hydrocarbons, of which asphalts, tars, pitches, and asphaltites are typical.

Asphalt - A dark brown to black cementitious material in which the predominating constituents are bitumens which occur in nature or are obtained in petroleum processing.

Asphalt cement - A fluxed or unfluxed asphalt specially prepared as to quality and consistency for direct use in the manufacture of bituminous pavements, and having a penetration at 77°F (25°C) of between 5 and 300, under a load of 100 g applied for 5 s.

Cut-back asphalt - Petroleum residiums which have been blended with distillates.

Anionic emulsion - A type of emulsion such that a particular emulsifying agent establishes a predominance of negative charges on the discontinuous phase.

Cationic emulsion - A type of emulsion such that a particular emulsifying agent establishes a predominance of positive charges on the discontinuous phase.

Liquid bituminous materials - Those having a penetration at 77°F (25°C), under a load of 50 g applied for 1 s, of more than 350.

II. SELECTION OF STABILIZER TYPE

INTRODUCTION

Stabilization of subgrade soils and aggregates by mechanical or chemical means is very common. The decision as to the proper form of stabilization (mechanical or chemical) as well as the selection of the proper chemical stabilizer is often made without the benefit of extensive field and laboratory testing. Ideally, field tests should be performed to determine the type or types and characteristics of the subgrade soils as well as to define the types and properties of borrow materials available. Laboratory tests should be performed to determine the engineering properties of mechanically stabilized and chemically stabilized soils and borrow materials. Cost and energy associated with providing the pavement structures designed with these materials should be calculated, based on engineering economic principles including first costs and maintenance and rehabilitation costs over a 20 to 30 year period (Appendices C and D). Except for large projects, this desired engineering approach is rarely undertaken. Therefore, simplified guidelines need to be established to direct the engineer to those stabilization techniques which appear most suitable for the particular situation.

This chapter will present criteria which can be used as a guide to select the proper type of chemical stabilizer. The decision of using mechanical or chemical stabilization is one of economy and an appreciation of the engineering advantages and disadvantages of the different types of stabilization. Advantages of chemical stabilization have been identified in Chapter I.

REVIEW OF EXISTING GUIDES

Several general guides have been published which assist the engineer in the proper selection of a stabilizer for a particular soil. A review of this literature is presented in Volume 2, Chapter II, of these guidelines. A summary is presented below.

Lime Stabilization

Experience has shown that lime will react with medium, moderately fine, and fine grained soils to produce decreased plasticity, increased workability, reduced swell, and increased strength (4). Generally speaking, those soils classified by AASHO as A-4, A-5, A-6, A-7, and some of the A-2-7 and A-2-6 soils are most readily susceptible to stabilization with lime. Soils classified according to the Unitied System as CH, CL, MH, ML, SC, SM, GC, GM, SW-SC, SP-SC, SM-SC, GW-GC, CP-GC, or GM-GC should be considered as potentially capable of being stabilized with lime.

Robnett and Thompson (4), based on experience gained with Illinois soils, have indicated that lime may be an effective stabilizer with clay contents (<2μ) as low as 7 percent and, furthermore, soils with a P.I. as low as 8 can be satisfactorily stabilized with lime (5). Air Force criteria indicate that the P.I. should be greater than 12, while representatives of the National Lime Association (6) indicate that a P.I. greater than 10 would be reasonable criteria to utilize.

Fly Ash Stabilization

Although fly ashes have been utilized for soil stabilization purposes in the United States since 1950, little definitive information is available which identifies soils which are most suitable for stabilization with fly ash, lime-fly ash, or cement-fly ash mixtures.

Fly ashes are normally used in stabilization operations to act as pozzolans and/or as fillers to reduce air voids in naturally occurring or blended aggregate systems. Since the particle size of the fly ash is normally larger than the voids in fine grained soils, the role as a filler is not appropriate for use in fine grained soils. Thus the only role for the fly ash in stabilization of fine grained soils is that of a pozzolan. Most clays (but not all clays) are pozzolanic in nature and thus do not require additional pozzolans. Thus, silts are generally considered the most suitable fine grained soil type for treatment with lime-fly ash or cement-fly ash mixtures.

Aggregates which have been successfully utilized in lime-fly ash mixtures include a wide range of types and gradations, including sands, gravels, crushed stones, and several types of slag. Lime-fly ash aggregate mixtures are often more economical to use than lime-fly ash fine grained soil mixtures. In addition these mixtures' coarser systems have greater resistance to frost action.

It should be pointed out that some fly ashes that are high in calcium oxide can be used with fine grained soils to form acceptable stabilized materials. These fly ashes are normally obtained from power plants utilizing Western United States coals.

Cement Stabilization

The Portland Cement Association (7, 8) indicates that all types of soils can be stabilized with cement. However, well-graded granular materials that possess sufficient fines to produce a floating aggregate matrix have given the best results.

Limits on Plasticity Index have been established by the Air Force. The P.I. should be less than 30 for sandy materials while the P.I. should be less than 20 and the Liquid Limit less than 40 for fine grained soils. This limitation is necessary to ensure proper mixing of the stabilizer. For gravel type materials a minimum of 45 percent by weight passing the No. 4 sieve is desirable. In addition, the P.I. of the soil should not exceed the number indicated from the following equation:

$$20 + \frac{50 - \text{Fines Content}}{4}$$

Information developed by the Bureau of Public Roads (9) indicates that cement should be used as a stabilizer for materials with less than 35 percent passing the No. 200 sieve and with a P.I. less than 20. Thus, this system implies that AASHO classified A-2 and A-3 soils can be best stabilized by cement while A-4, A-5, A-6, and A-7 soils can be best stabilized by lime.

Asphalt Stabilization

Some of the earliest criteria for bituminous stabilization were developed by the Highway Research Board Committee on Soil-Bituminous Roads. These criteria were revised and published by Winterkorn (10) and the American Road Builders Association (11).

The Asphalt Institute (12), Chevron Asphalt Company (13), Douglas Oil Company (14), Materials Research and Development (15) and the University of Illinois (16) have developed criteria. The consensus of their work indicates the maximum percent passing the No. 200 sieve should be less than 25 percent, the plasticity index less than 6, Sand Equivalent less than 30, and the product of the plasticity index and the percent passing the No. 200 sieve less than 72. In general, materials that are suitable for asphalt treatment include AASHO-classified A-1-2,A-1-b, A-2-4, A-2-6, A-3, A-4, and low plasticity A-6 soils, and soils classified by the Unified Classification System as SW, SP, SW-SM, SP-SM, SW-SC, SP-SC, SM, SC, SM-SC, GW, GP, GW-GM, GP-SM, GW-GB, GP-GC, GC, and GM-GC provided certain plasticity and grading requirements are met (16).

Combination Stabilizers

Combination stabilizers discussed in this section include lime-cement and lime-asphalt.

Robnett and Thompson (16) have reviewed the literature associated with combination stabilizers and have suggested that AASHO classified A-6 and A-7 soils and certain A-4 and A-5 soils can be economically treated.

The main purpose cited for using combination stabilizers is to reduce plasticity and increase workability so the soil can be intimately mixed and effectively stabilized. As noted, lime is the pretreatment stabilized followed by cement or asphalt.

The advantage of using lime in certain asphalt stabilization operations is to prevent stripping of asphalts from certain aggregates in the presence of water. In addition, lime can be used to reduce the plasticity index and thus provide better mixing and coating.

Portland cement and lime have been utilized in emulsion stabilization operations to help control emulsion break.

SUMMARY OF CRITERIA FOR SELECTING STABILIZING AGENTS

Criteria have been presented which represent a wide range of opinion as to the types of soils that can be stabilized by certain stabilizers. Most published information gives reference to soils classified either by the AASHO or Unified Soil Classification Systems; however, the authors feel that a more appropriate separation of soils for stabilization can be made utilizing Atterberg Limits and sieve analysis. It should be remembered that both Atterberg Limits and sieve analysis are relatively easy tests to perform in the laboratory and both are a necessary input for the AASHO and Unified Soil Systems. Figure 1 presents guidelines that can be used by the engineer to select the most suitable stabilizer for a given soil (17, 18). Once the stabilizer is selected, detailed laboratory tests should be performed as outlined in those chapters associated with the individual stabilizers and contained in Volume II of the manual.

Once the type or types of stabilizers have been selected for a particular soil, the engineer should be aware of certain climatic limitations that may restrict the use of the stabilizer. In addition safety considerations should be understood by the engineer prior to the selection of the stabilizer. General climatic limitations and construction safety precautions are given on Table 1.

Table 1. Climatic Limitations and Construction Safety Precautions

Type of Stabilizer	Climatic Limitations	Construction Safety Precautions
Lime and Lime-Fly Ash	Do not use with frozen soils Air temperature should be 40 F (5 C) and rising Complete stabilized base construction one month before first hard freeze Two weeks of warm to hot weather are desirable prior to fall and winter temperatures	Quicklime should not come in contact with moist skin Hydrated lime [$Ca(OH)_2$] should not come in contact with moist skin for prolonged periods of time Safety glasses and proper protective clothing should be worn at all times
Cement and Cement-Fly Ash	Do not use with frozen soils Air temperature should be 40 F (5 C) and rising Complete stabilized layer one week before first hard freeze	Cement should not come in contact with moist skin for prolonged periods of time Safety glasses and proper protective clothing should be worn at all times
Asphalt	Air temperature should be above 32 F (0 C) when using emulsions Air temperatures should be 40 F (5 C) and rising when placing thin lifts (1-inch) of hot mixed asphalt concrete Hot, dry weather is preferred for all types of asphalt stabilization	Some cutbacks have flash and fire points below 100 F (40 C) Hot mixed asphalt concrete temperatures may be as high as 350 F (175 C)

1 in. = 2.54×10^{-2} m

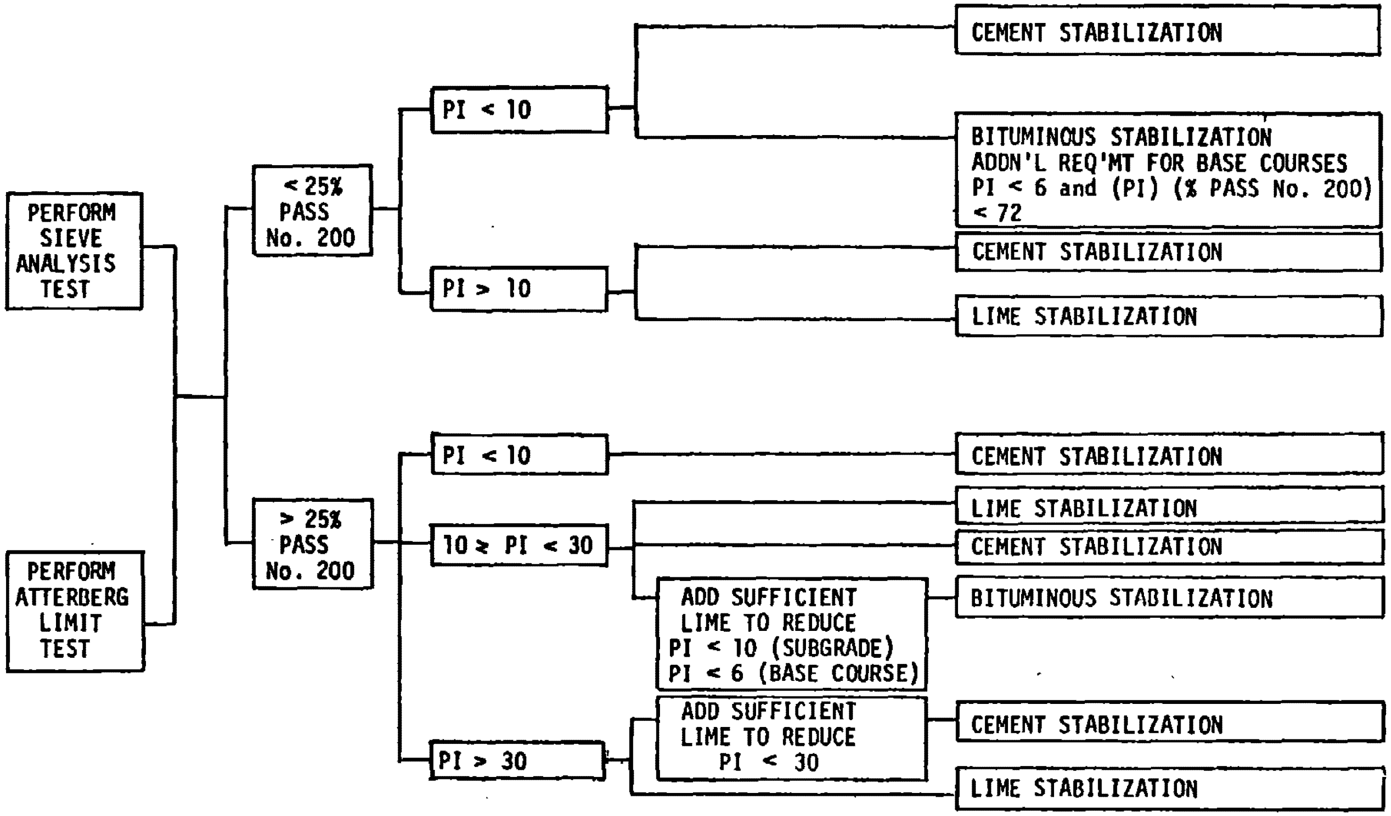


Figure 1. Selection of stabilizers (after references 17 and 18).

III. PAVEMENT THICKNESS DESIGN

INTRODUCTION

There have been many efforts over the past 30 years to develop procedures for pavement thickness design that are based on rational approaches. Some of these procedures are widely used and a few have become firmly established within certain design organizations.

Although each of the methods available was developed for various conditions and each has its own merits, those suggested for use in this manual are:

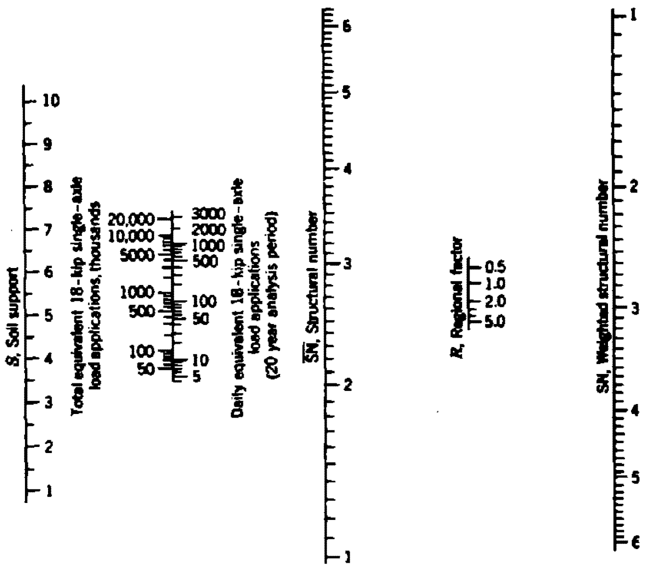
1. AASHTO Interim Guide and
2. Multilayered elastic analysis.

These general methods have been adopted for a wide range of conditions and materials and are used by many agencies. The AASHO approach (19) was originally developed from the AASHO Road Test and has been modified by several studies. The multilayer approach was developed as an analysis tool and remains so today. However, several agencies have utilized the versatility of the layered system to develop design systems based on suitable critieria for stresses and strains for various pavement layers. The design method developed by Shell (20) has seen increasing use and has been updated (21). Chevron (22) has also developed a useful design approach that includes materials usch as cement-modified asphalt emulsion mixtures. Many researchers have improved the usefulness of the elastic layer approach by developing better data for modulus and Poisson's ratio as well as limiting criteria to reduce rutting and fatigue damage.

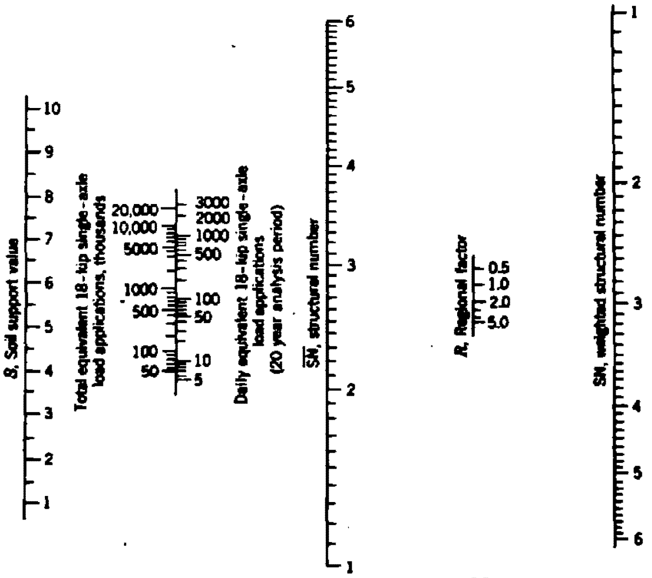
This chapter includes a summary of the design methods and discusses the type of information needed for input. Where appropriate, suggestions are made for typical values of such inputs for lime, lime-fly ash, cement, asphalt as well as untreated materials. A brief summary of several other design methods is also given at the conclusion of the chapter.

AASHO INTERIM GUIDE

The pavement design procedure recommended by the AASHO (currently called AASHTO for American Association of State Highway and Transportation Officials) is based on data developed during the AASHO Road Test conducted in Ottawa, Illinois, and supplemented and modified by data from other road tests, from other design procedures, and from theoretical relationships developed in recent research. The design procedure is presented in this report in the form of nomographs (Figure 2) for



Design chart for flexible payments, $P_t = 2.0$



Design chart for flexible pavements, $P_t = 2.5$

1 ksi = 4.448×10^3 N

Figure 2. AASHO flexible-pavement design ncmographs(19).

ease in the solution of the design equation. The equations represented by these nomographs were developed on the basis of the following assumptions (19):

1. That the basic equations developed from the AASHO road test are a valid representation of the relationship between loss in serviceability, traffic, and pavement thickness. In these equations, loss in serviceability* is expressed in terms of reduction of serviceability index; traffic is converted to equivalent 18-kip (80 kN) single-axle load applications; and pavement thickness is represented by a structural number.

2. That the basic equations developed from the AASHO road test for a single type of roadbed soil may be extended to apply to any roadbed soil by means of a soil support scale developed for this purpose.

3. That the basic equations developed from the AASHO road test for repeated applications of uniform traffic may be extended to apply to mixed traffic by conversion to equivalent 18-kip (80 kN) single-axle loads.

4. That the basic equations developed from the AASHO road test for a single environmental condition may be extended to apply to other environmental conditions by means of an appropriate Regional factor.

5. That the basic equations developed from the AASHO Road Test for the subbase, base, and surfacing materials used in constructing the test road may be extended to apply to other materials by assignment of appropriate layer coefficients (a_1, a_2, a_3).

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*Serviceability - the ability at time of observation of a pavement to serve high-speed, high-volume automobile and truck traffic.

Present Serviceability Rating (PSR) - the mean value of the independent subjective ratings by members of a special panel for the AASHO Road Test as to the serviceability of a section of highway. The members of the panel included highway specialists representing many fields of interest and concern in highways.

Serviceability Index (PSI) - a number derived by formula for estimating the serviceability rating from measurements of certain physical features of the pavement.

6. That the basic equations developed from the AASHO road test for accelerated applications of traffic during the two-year period may be extended to apply to applications of traffic during an extended period of time (up to 20 years).

7. That uniform and high-quality construction will be obtained, particularly with respect to density, gradation, and quality of materials, and smoothness of the pavement surface, both transversely and longitudinally.

The final design equation relates the number of equivalent 18-kip (80 kN) single-axle load repetitions (Wt_{18}) required to reach a terminal serviceability index (P_t) for any given pavement structure (SN), layer coefficients (a_1, a_2, a_3), Regional factor (R), and subgrade soil support (S). The actual equation is most easily used in nomograph form (Figure 2) and is not presented here.

A guide to the evaluation of the essential elements in this design method using stabilized materials is presented as follows:

Terminal Serviceability Index (P_t)

The terminal serviceability index P_t is the lowest serviceability that will be tolerated on the road at the end of the traffic analysis period before resurfacing or reconstruction is warranted. The index or rating numbers are on a scale of 1 through 5. These numbers were developed by subjective means using panels of people with varying backgrounds and experience. PSI ratings used are: (0-1) very poor, (1-2) poor, (2-3) fair, (3-4) good, and (4-5) very good. New high standard bituminous surfaces have serviceability indexes of about 4.7. For major highway facilities, a terminal serviceability P_t of 2.5 is recommended while a P_t of 2.0 is suggested for low traffic volume roads. Figure 2 is for these two limiting conditions.

Typical Strength Coefficients

The solution of the design equation is in terms of a structural number (SN). The SN is defined as an index number derived from an analysis of traffic, subgrade soil conditions, and regional factor that may be converted to thickness of various flexible pavement layers through the use of suitable layer coefficients related to the type of material being used in each layer. The layer coefficient is the empirical relationship between SN for a pavement structure and layer thickness, which expresses the relative ability of a material to function as a structural component of the pavement.

The SN is given by the relation:

$$SN = a_1D_1 + a_2D_2 + a_3D_3$$

where a_1, a_2, a_3 = layer coefficients representative of surface, base, and subbase course, respectively,

D_1, D_2, D_3 = actual thickness in inches of surface, base, and subbase courses, respectively.

This relationship indicates that to achieve a specified structural capacity, there is an inverse linear relationship between the structural coefficient and the thickness of each layer in a flexible pavement system. Usually, there are minimum material standards associated with the assigned coefficients. In addition, a range of coefficients can be used to reflect different qualities for specific materials.

Also, because of the widely varying environments, traffic, and construction practices, it is suggested that each design agency establish layer coefficients applicable to its own practices and based on its own experience. Suggested values such as shown in Table 2 for stabilized materials may be used.

Soil Support

The basic equation developed from the AASHO Road Test is valid for only one value of soil support, that representing the subgrade soil condition at the road test site. In order to make the design procedure applicable to other roadbed soils, it was necessary to assume a soil support scale S to represent the variety of soils which would be encountered at other sites. The starting point of this scale was a soil support of 3.0 which represented the roadbed soils at the test site. A second point on the S scale was developed by an examination of the performance of thick crushed-rock base selected to minimize the effect of the roadbed soil. This value was assigned S = 10.0, and intermediate values were based upon a linear relation between these two points such that:

$$\log W_{t_{18}} = \log N_{t_{18}} + K\ (Si-So)$$

where Si = Soil support value for any condition i

So = Soil support value for Road Test Conditions

$W_{t_{18}}$ = Total load applications for condition i

$N_{t_{18}}$ = Total load applications for Road Test Conditions

K = Regression constant (K = 0.372)

Examples of relationship between soil support S value and other laboratory test procedures (CBR, dynamic and static, R-value and AASHTO T-193) are shown in Figures 3 and 4.

Table 2. Structural Layer Coefficients Developed from Various Sources.

STABILIZER	LAYER	MATERIAL	COEFFICIENT (note)
Asphalt	^{a}Surface	Road mix (low stability)	0.20(a) 0.15(k)
		Plant mix (high stabil.)	0.44(8) 0.30(h) 0.25 - 0.34(i) 0.30(k)
		Sand asphalt	0.40(a,d,n) 0.20(h) 0.25(e) 0.28(g)
	^{b}Base	Bituminous treated	0.175 - 0.21(g)
		coarse graded	0.34(a,b) 0.24(m) 0.30(d)
		sand asphalt	0.30(a) 0.25(d)
		Sand gravel	0.25 - 0.34(e)
		Asphalt stabilized	0.10(f)
Untreated	^{b}Base	Sandy gravel	0.17(a,b)
		Crushed stone	0.14(*)
	^{c}Subbase	Sandy gravel	0.11(*)
		Sand or sandy clay	0.05 - 0.10(a)
Lime	^{b}Base	Lime-treated	0.15 - 0.39(a,n) 0.15 - 0.20(h)
	^{c}Subbase	Lime-treated clay-gravel	0.18(c) 0.14
		Lime-treated soil	0.11(p)
Lime - Fly ash	^{b}Base	Lime - Fly ash base	0.25 - 0.30(c)
Cement	^{b}Base	7-day compressive strength:	
		650 psi or more	0.23(a,b,n,k)
		400-650 psi	0.20(a,n) 0.17(k)
		400 psi or less	0.15(a,n) 0.12(k)
		Soil cement	0.20(f,ℓ)
		Gravel	0.17(j)
		Cement-treated	0.15 - 0.25(p)

1 psi = 6.89 x 10^3 Pa

Notes for Table 2

* Established from AASHO Road Test

a From AASHO Interim Guide, 1972

b This value has been estimated from AASHO Road Test data, but not to the accuracy of those marked with an asterisk.

c NCHRP Sythesis of Highway Practice, No. 37, "Lime-Fly Ash-Stabilized Bases and Subbases." (R-1)

d Alabama (from a above)

e Arizona (from a above)

f Deleware

g Minnesota

h Montana

i Nevada

j New Hampshire

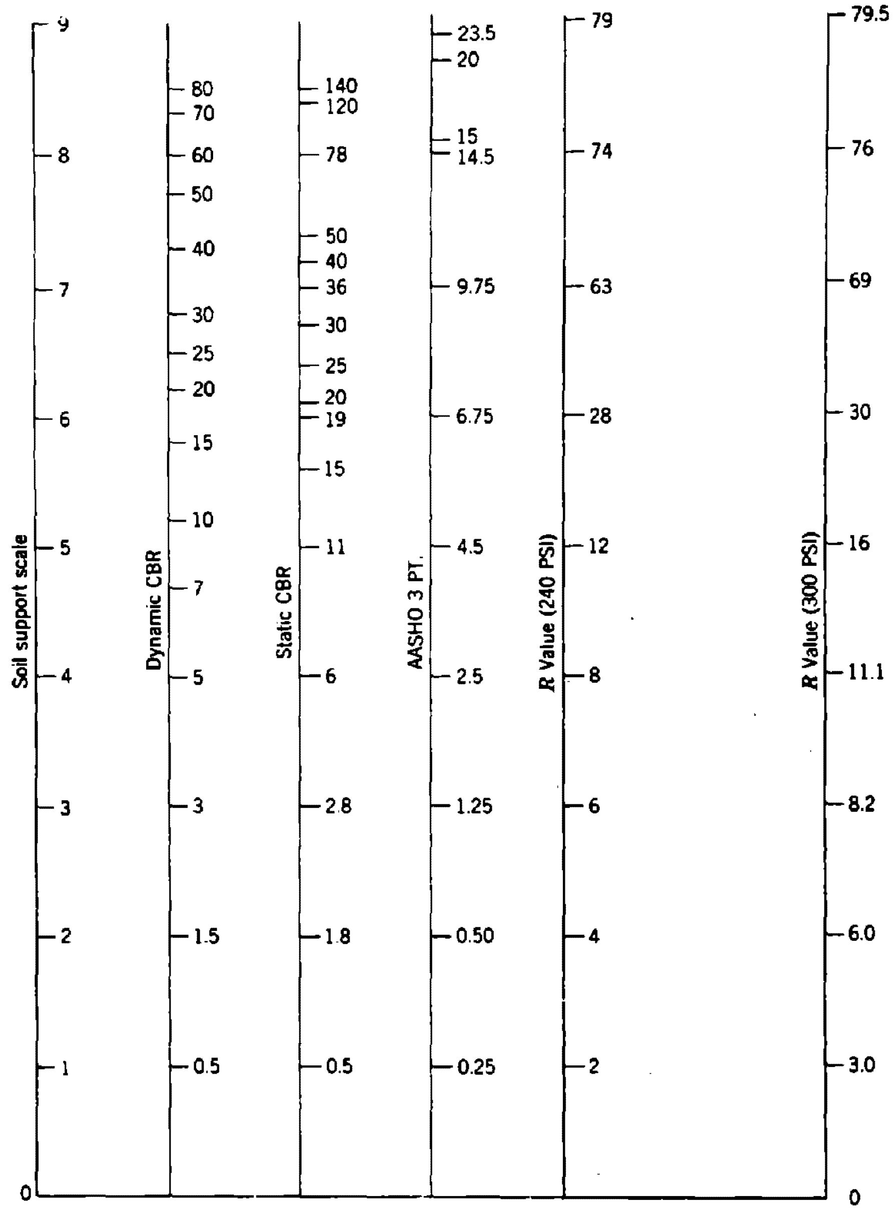
k New Mexico

ℓ Pennsylvania

m South Dakota

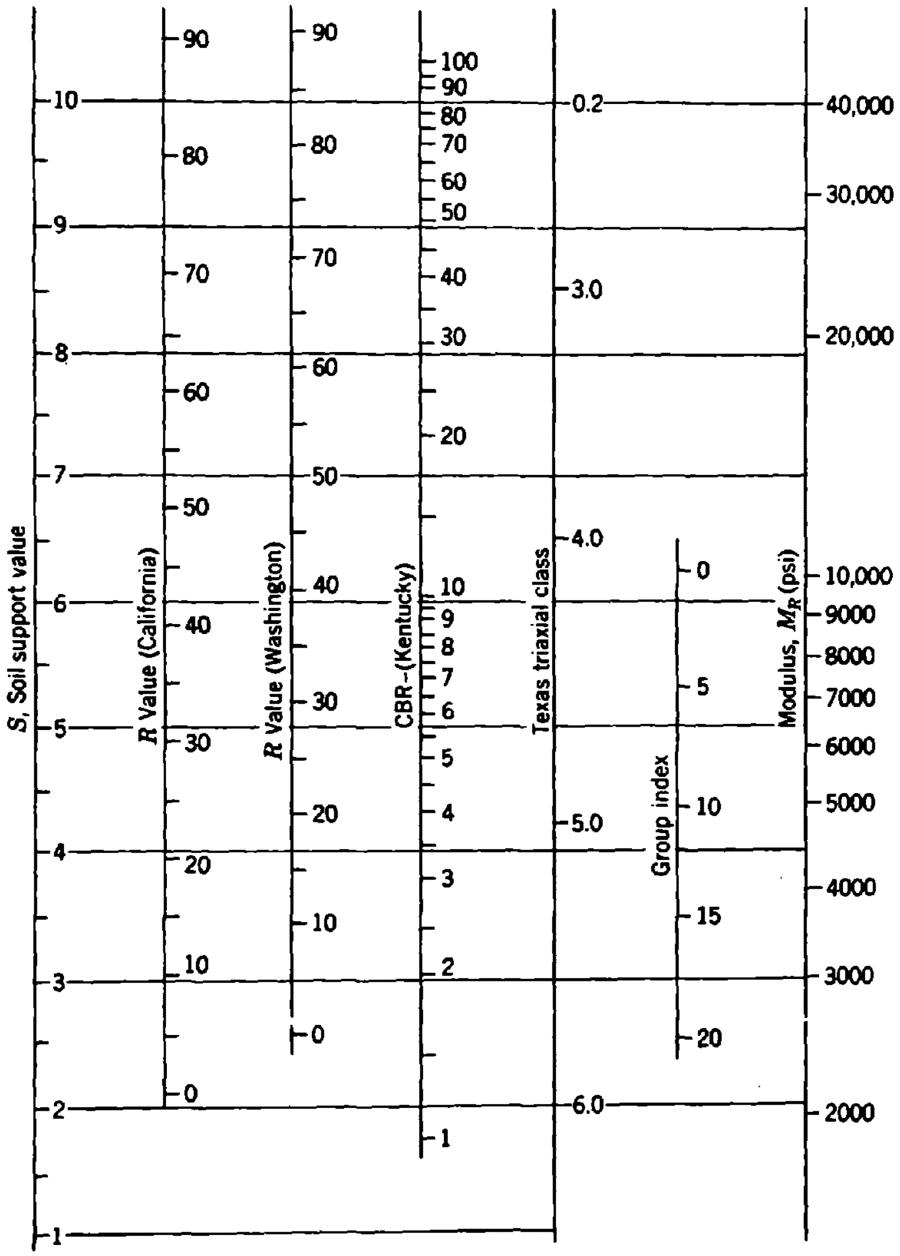
n Wisconsin

p. Wyoming



1 psi = 6.89 x 10^3 Pa

Figure 3. Soil support value correlations (19).



1 psi = 6.89×10^3 Pa

Figure 4. Soil support value correlations(19).

Regional Factor

The regional factor R was included in the design guide equation to make it applicable for design of pavements in areas with climatic and environmental conditions different from those at the AASHO Road Test site. Based upon an analysis of the Road Test results dealing with the rate of loss of serviceability during various climatic periods during the testing, typical values of R were developed and given by the AASHO guide as follows:

Condition	R-Value
Roadbed materials frozen to depth of 5" (130 mm) or more	0.2 to 1.0
Roadbed materials dry, summer and fall	0.3 to 1.5
Roadbed materials et, spring thaw	4.0 to 5.0

Apart from these, many other factors such as rainfall, subsurface drainage, topography, etc., have been used by states to estimate regional factors. In general, the regional factor R should not exceed about 4.0 or be less than about 0.5 for conditions in the United States except certain areas of Alaska.

Traffic Loading

To use the AASHO design guide, mixed truck traffic must be converted to an equivalent number of 18-kip (80 kN) single-axle loads. The procedure for accomplishing this conversion includes:

1. Derivation of Traffic Equivalence Load Factors
2. Conversion of mixed Traffic to equivalent 18-kip single-axle load applications
3. Lane distribution considerations

Truck traffic may be equated to 18-kip (80 kN) load applications, if a common 20-year traffic analysis period is selected, or it may be expressed as the total 18-kip (80 kN) load applications within the traffic analysis period. The equivalency factors, and hence total load applications W_{t18}, are a function of terminal serviceability P and structural number SN. For most design problems, an SN value of 3.0 may be assumed for the equivalency analysis. This value will normally result in overestimation of W_{t18} but in general, the resulting error will be insignificant. AASHO equivalence factors for flexible pavements are as shown on Table 3.

Table 3. AASHO Equivalence Factors - Flexible Pavement (19)

Single Axles, P_t = 2.0

Axle Load (kips)	Structural Number, SN					
	1	2	3	4	5	6
2	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
4	0.002	0.003	0.002	0.002	0.002	0.002
6	0.01	0.01	0.01	0.01	0.01	0.01
8	0.03	0.04	0.04	0.03	0.03	0.03
10	0.08	0.08	0.09	0.08	0.08	0.08
12	0.16	0.18	0.19	0.18	0.17	0.17
14	0.032	0.34	0.35	0.35	0.34	0.33
16	0.59	0.60	0.61	0.61	0.60	0.60
18	1.00	1.00	1.00	1.00	1.00	1.00
20	1.61	1.59	1.56	1.55	1.57	1.60
22	2.49	2.44	2.35	2.31	2.35	2.41
24	3.71	3.62	3.43	3.33	3.40	3.51
26	5.36	5.21	4.88	4.68	4.77	4.96
28	7.54	7.31	6.78	6.42	6.52	6.83
30	10.38	10.03	9.24	8.65	8.73	9.17
32	14.00	13.51	12.37	11.46	11.48	12.17
34	18.55	17.97	16.30	14.97	14.87	15.63
36	24.20	23.30	21.16	19.28	19.02	19.93
38	31.14	29.95	27.12	24.55	24.03	25.10
40	39.57	38.02	34.34	30.92	30.04	31.25

Tandem Axles, P_t = 2.0

Axle Load (kips)	Structural Number SN					
	1	2	3	4	5	6
10	0.01	0.01	0.01	0.01	0.01	0.01
12	0.01	0.02	0.02	0.01	0.01	0.01
14	0.02	0.03	0.03	0.03	0.02	0.02
16	0.04	0.05	0.05	0.05	0.04	0.04
18	0.07	0.08	0.08	0.08	0.07	0.07
20	0.10	0.12	0.12	0.12	0.11	0.10
22	0.16	0.17	0.18	0.17	0.16	0.16
24	0.23	0.24	0.26	0.25	0.24	0.23
26	0.32	0.34	0.36	0.35	0.34	0.33
28	0.45	0.46	0.49	0.48	0.47	0.46
30	0.61	0.62	0.65	0.64	0.63	0.62
32	0.81	0.82	0.84	0.84	0.83	0.82
34	1.06	1.07	1.08	1.08	1.08	1.07
36	1.38	1.38	1.38	1.38	1.38	1.38
38	1.76	1.75	1.73	1.72	1.73	1.74
40	2.22	2.19	2.15	2.13	2.16	2.18
42	2.77	2.73	2.64	2.62	2.66	2.70
44	3.42	3.36	3.23	3.18	3.24	3.31
46	4.20	4.11	3.92	3.83	3.91	4.02
48	5.10	4.98	4.72	4.58	4.68	4.83

Table 3. AASHO Equivalence Factors - Flexible Pavement (Cont'd) (19)

Single Axles, P_t = 2.5

Axle Load (kips)	Structural Number, SN					
	1	2	3	4	5	6
2	0.0004	0.0004	0.0003	0.0002	0.0002	0.0002
4	0.003	0.004	0.004	0.004	0.003	0.002
6	0.01	0.02	0.02	0.01	0.01	0.01
8	0.03	0.05	0.05	0.04	0.03	0.03
10	0.08	0.10	0.12	0.10	0.09	0.08
12	0.17	0.20	0.23	0.21	0.19	0.18
14	0.33	0.36	0.40	0.39	0.36	0.34
16	0.59	0.61	0.65	0.65	0.62	0.61
18	1.00	1.00	1.00	1.00	1.00	1.00
20	2.61	1.57	1.49	1.47	1.51	1.55
22	2.48	2.38	2.17	2.09	2.18	2.30
24	3.69	3.49	3.09	2.89	3.03	3.27
26	5.33	4.99	4.31	3.91	4.09	4.48
28	7.49	6.98	5.90	5.21	5.39	5.98
30	10.31	9.55	7.94	6.83	6.97	7.79
32	13.90	12.82	10.52	8.85	8.88	9.95
34	18.41	16.94	13.74	11.34	11.18	12.51
36	24.02	22.04	17.73	14.38	13.93	15.50
38	30.90	28.30	22.61	18.06	17.20	18.98
40	39.26	35.89	28.51	22.50	21.08	23.04

Tandem Axles, P_t = 2.5

Axle Load (kips)	Structural Number, SN					
	1	2	3	4	5	6
10	0.01	0.01	0.01	0.01	0.01	0.01
12	0.02	0.02	0.02	0.02	0.01	0.01
14	0.03	0.04	0.04	0.03	0.03	0.02
16	0.04	0.07	0.07	0.06	0.05	0.04
18	0.07	0.10	0.11	0.09	0.09	0.07
20	0.11	0.14	0.16	0.14	0.12	0.11
22	0.16	0.20	0.23	0.21	0.18	0.17
24	0.23	0.27	0.31	0.29	0.26	0.24
26	0.33	0.37	0.42	0.40	0.36	0.34
28	0.45	0.49	0.55	0.53	0.50	0.47
30	0.61	0.65	0.70	0.70	0.66	0.63
32	0.81	0.84	0.89	0.89	0.86	0.83
34	1.06	1.08	1.11	1.11	1.09	1.08
36	1.38	1.38	1.38	1.38	1.38	1.38
38	1.75	1.73	1.69	1.68	1.70	1.73
40	2.76	2.67	2.49	2.43	2.51	2.61
42	2.76	2.67	2.49	2.43	2.51	2.61
44	3.41	3.27	2.99	2.88	3.00	3.16
46	4.18	3.98	3.58	3.40	3.55	3.79
48	5.08	4.80	4.25	3.98	4.17	4.49

Use of the Design Charts

The flexible pavement design equation shown as nomographs in this manual was developed from the basic AASHO road test equation, modified as discussed in the previous section. The design equation is presented in the form of two nomographs for simplicity of application (Figure 2). For design of temporary roads or for stage construction, it is suggested that an appropriate traffic analysis period be used and W_{t18} be calculated.

Once the decision has been made relative to the terminal serviceability index P_t, and the appropriate design chart has been selected, the following values must be determined before the design charts can be used:

a. Representative values of soil support for the roadbed soil

b. The total or daily equivalent 18-kip (80 kN) single-axle loads estimated for the design lane for the traffic analysis period

c. The regional factor applicable to the site.

The chart requires two applications of a straight edge for each solution. First, the soil support value of the roadbed soil (on the left side) and the total or daily 18-kip (80 kN) single-axle loads for the traffic analysis period (left side of second scale) are used to solve for the unweighted structural number (center scale). This unweighted structural number is used with the selected regional factor (4th scale) to solve for the design SN (right scale) applicable to the total pavement structure. Suitable designs are those whose combinations of material types and thicknesses satisfy the general equation:

$$SN = a_1D_1 + a_2D_2 + a_3D_3$$

Applicability to Stabilized Bases

The use of the AASHO Interim guide for asphalt concrete pavements to design sections containing stabilized layers merely requires the determination of the structural number from Figure 2 and the use of the appropriate coefficient a_2 or coefficients a_2 and a_3 if different treatments are contemplated with depth. While this procedure has considerable appeal because of its simplicity, there are a number of limitations. From the standpoint of type of stabilization, for example, the coefficients a_2 and a_3 will vary considerably. The level of treatment and type of soil being stabilized will require careful selection of coefficients from sources such as those in Table 2. In addition, the procedure is limited to highway-type loadings. An example problem utilizing this approach is shown in Chapter V.

Fixed values for structural coefficient or gravel equivalency factors for stabilized soils do not seem warranted since the engineering properties of the mixture, subgrade support, and the structural makeup of the pavement would influence the behavior and performance of the stabilized layers. For example, Thompson (24), in a document prepared for the Illinois Division of Highways, has demonstrated that for typical low-volume road pavement design, the structural coefficient would vary over a range from 0.12 to 0.26 depending on mixture strength and subgrade support. An extensive study (25) of soil-lime pavements in Louisiana in which structural coefficients were back-calculated from present serviceability index data suggests a similar broad range of coefficients for soil-lime mixture base courses.

MULTILAYERED ELASTIC DESIGN

Until the early 1960's the design and construction of pavements had been primarily based on empiricism and experience, with theory playing only a subordinate role. The changes resulting from heavier wheel loads, higher traffic levels, and the recognition of various independent distress modes contributing to pavement failures have led to the search for a more rational method of pavement design in the last several years. The use of multilayered elastic theory in pavement design is gaining ground as this concept is being incorporated into several design procedures.

Basically, layered-elastic theory assumptions as to the state of stress or strain in the pavement, are summarized as follows (26):

1. Each layer of a pavement acts as a horizontally continuous, isotropic, homogeneous, linearly elastic medium;
2. Each layer has a finite thickness except for the lower layer, and all are infinite in the horizontal directions;
3. The surface loading can be represented by uniformly distributed vertical stresses over a circular area;
4. The interface conditions between layers can be represented as either perfectly smooth or perfectly rough;
5. Inertial forces are negligible;
6. Deformations throughout the system are small; and
7. The stress solutions are characterized by two material proper--ties--Poisson's ratio μ and elastic modulus E.

From the adoption of all or part of these assumptions, several computer programs (see later section) have been developed to perform elastic-layered theory claculations. There are some typical basic input characteristics and design elements that are common to these computer programs and peculiar to layered elastic design.

Typical Materials Properties

In order to use elastic layered theory for the design of pavements, it is necessary to carefully select the input parameters. The following three considerations must be kept in mind since they are important in the design analysis:

1. Determination of representative modulus values for each of the pavement layers
2. Variation in the traffic loading
3. Variation in environmental conditions

Developing conceptual procedures for each of these factors is further complicated due to the interaction among them. For example, due to stress sensitivity of base, subbase, and subgrade materials, different modulus values need to be used for these layers for different load magnitudes. Therefore the load condition should be considered when selecting moduli to account for the stress sensitivity. The approach recommended is to compute variations in one subsystem (e.g. modulus of layers) assuming the other subsystems (e.g. traffic load and environment) remain constant. Thus, a range of each variable can be utilized to determine the relative importance of each.

In the elastic layered design method, the material properties which must be determined are the elastic modulus and Poisson's ratio of each layer. In general, the materials in pavements that are stabilized are in the base and subbase layers. Ideally, these materials should be tested for modulus values, but in most instances this would be impractical. Therefore, an estimate of the modulus of the stabilized material can be made such as shown in Table 4 (27). Values of Poisson's ratio for the stabilized bases and subbase materials are also included.

In any case, where there is need for laboratory testing, the method of testing the modulus values should reproduce field conditions as accurately as possible. For this purpose, the dynamic triaxial test is becoming widely accepted. There are two different versions of this test with the dynamic modulus test generally being used for asphalt concrete and the resilient modulus test for granular materials and subgrades (references 28 and 29).

Because of the sensitivity of modulus values to such variables as stabilization as well as soil type, level of treatment, age, and temperatures (for asphalt-treated materials), particular relationships are often more useful than data such as shown in Table 4. Most fine-grained soil will have characteristic curves similar to those shown in Volume 2, Chapter III (Figure 10). Figures 5 and 6 illustrate the

Table 4. Approximate Elastic Parameter Values for Stabilized Pavement Materials.

MATERIAL	MODULUS OF ELASTICITY PSI	POISSON'S RATIO	
Asphalt Treated Base	100,000 - 600,000	Low Stiffness: High Stiffness:	0.45 0.35
Cement Treated Base	Uncracked: up to 2,000,000		0.20
	Cracked: Down to values for untreated granular base material		0.30
Lime - Fly Ash (R-1)	1,500,000 - 2,500,000	Low stress level High stress level:	0.08 0.30
Lime Treated Base	Uncracked: up to 500,000		0.15
Soil Lime * Mixtures for Compressive Strength Range, psi			
100-200	25,000 - 100,000		0.15
200-400	100,000 - 300,000		0.15
> 400	300,000+		0.15

*For mixtures with strengths in excess of 400 psi, use the following relation for modulus:

$$E_{flexure} = 1.15S - 140$$

where E - flexural modulus, ksi

S = compressive strength, psi

Soil cement mixture:
see Table 20 in Volume 2 for unique relationships.

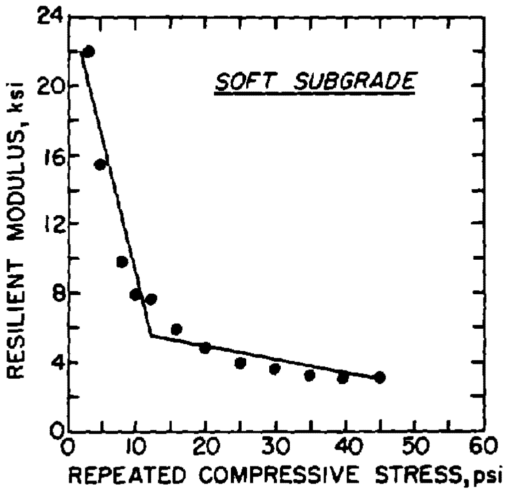
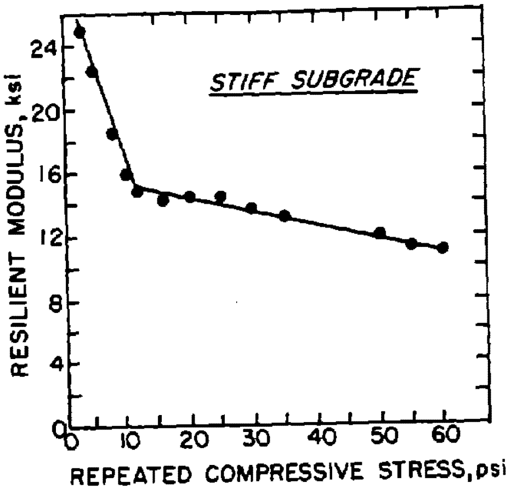


Figure 5. Resilient response - soft subgrade soil.



1 psi = 6.89 x 10^3 Pa
1 ksi = 6.89 x 10^6 Pa

Figure 6. Resilient response - stiff subgrade soil.

effect of varying subgrade quality. Various levels and types of cement treatment result in a wide range of modulus values as shown in Volume I, Chapter V (Figure 29). Asphalt-bound materials are sensitive to both temperature and time of loading as noted in Volume I Chapter VI (Figure 36 and 38). For emulsified-asphalt mixtures that are not fully cured, one must allow for reduced modulus as shown in Figure 7. However, as indicated in Volume I, Chapter VII (Figures 43 and 44), the curing of cement-modified emulsion mixtures may be accelerated and higher modulus values can be utilized during the early life of the pavement.

Unbound granular materials, whether they are in the pavement layers or subgrade, should be evaluated over a range of confining stresses in order to account for stress dependency. Figure 8 shows a typical relationship.

In addition to approximate values shown in Table 4, correlations have been developed for relating resilient or elastic modulus values to other test parameters. For example, Figures 3 and 4 show several soil strength values. Other correlations can be compared to soil classification as shown in Figure 9.

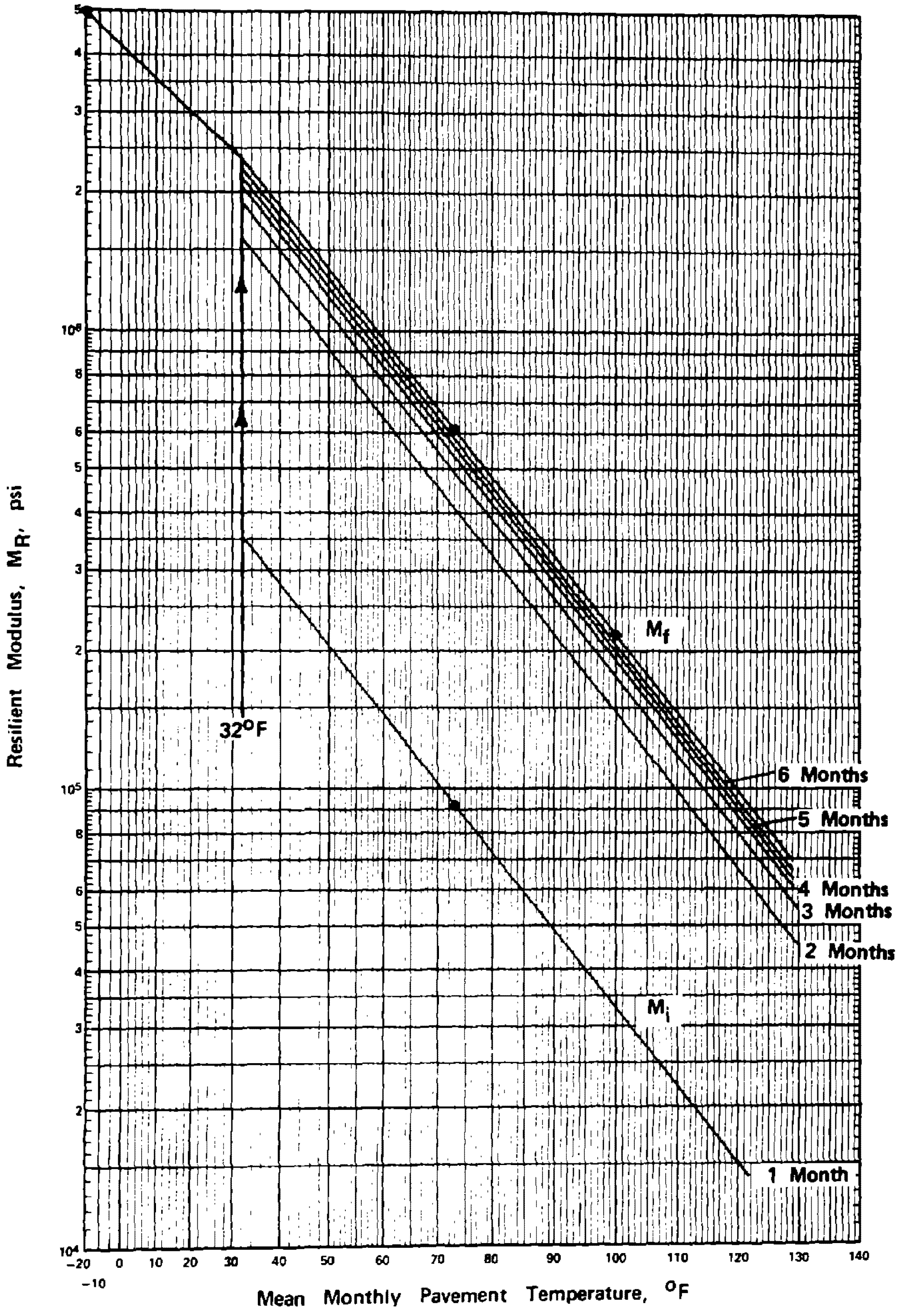
Traffic Loading

In using elastic layered theory, often only one load condition may be analyzed per program run, although others can be added by superposition or by the use of recently developed programs such as ELSYME. Recognition of the complicated and expensive procedure in separately analyzing each load condition has led many design agencies to develop wheel load equivalency factors where the different traffic loads are related to a standard load by a multiplication factor. Perhaps the most widely used wheel load equivalency factors are those developed at the AASHO Road test. These wheel load equivalency factors were developed based upon empirical data collected during the road test.

Another rational basis for calculating wheel load equivalency factors is based upon calculating the critical strain in an asphalt concrete layer for the standard load. Then a fatigue curve for asphalt concrete and Minor's hypothesis are used to determine the wheel load equivalency factor. The wheel load equivalency factors determined in this manner are similar to the AASHO wheel load equivalency factors. Thus, both provide rational equivalency factors that will reduce the variation of traffic loading to a single load condition. Traffic Equivalency factors developed during the AASHO road test can be found in the AASHO Interim Guide (19).

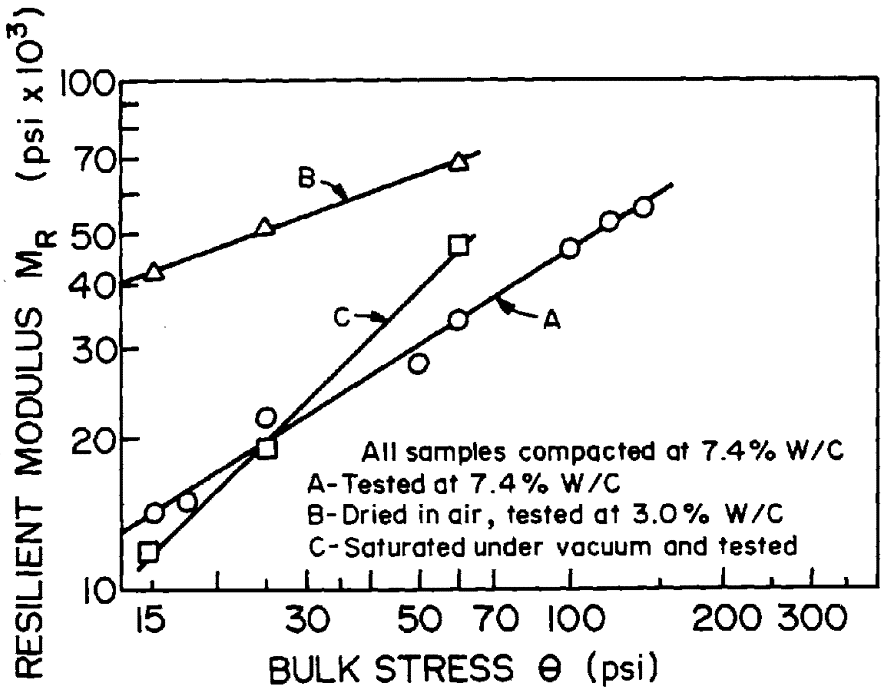
Design Criteria

In order to use elastic layer theory for pavement design, it is necessary to have models for relating the output from elastic layered theory (i.e., stresses, strains, and displacements) to pavement behavior



1 psi = 6.89 x 10^3 Pa

Figure 7. Modulus-pavement temperature relationship for emulsified asphalt mixes (22).



1 psi = 10^3 Pa

Figure 8. Resilient modulus vs. bulk stress relationship for untreated base material.

(e.g., performance, cracking, rutting). Such models may be described as behavior functions. Since elastic layer theory can be used to compute only the effects of traffic loads, it is logical to develop functions for only traffic-associated pavement behavior such as fatigue cracking. Based upon this limitation, most of the principles of layered elastic design are based upon limiting strains in the stabilized layer or layers (fatigue analysis) and permanent deformation (rutting) in the subgrade. The critical points for these limitations are noted in Figure 10. The procedure recommended here is for limiting strain in the asphalt-bound layer; however, a limiting response may be found to exist in any one of the stabilized layers.

Fatigue Resistance

Fatigue is a phenomenon of repetitive load-induced cracking due to repeated stress or strain level below the ultimate strength of the material. In practice, pavements are subjected to a wide range of loadings; accordingly, a cumulative damage hypothesis can be used to analyze fatigue data. One of the simplest of such hypotheses is the linear

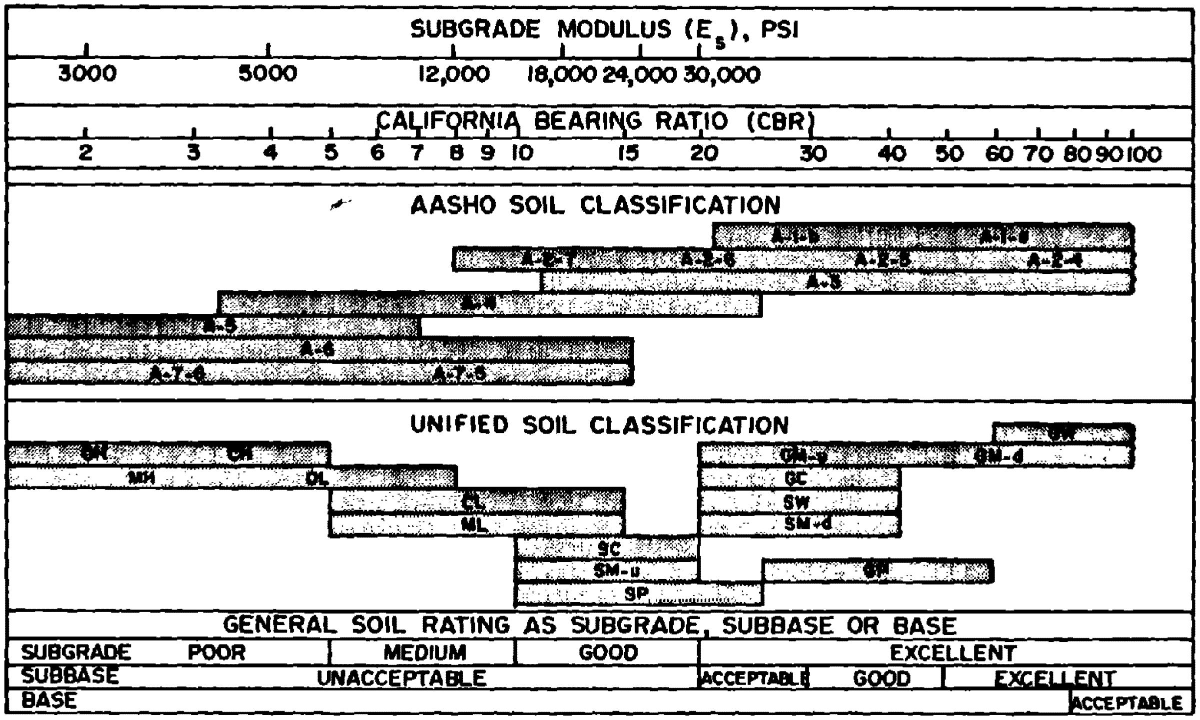
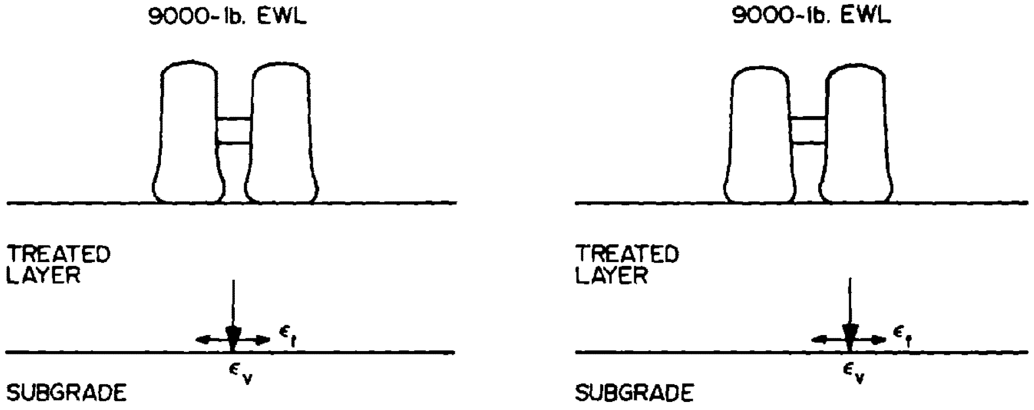


Figure 9. Approximate correlation of subgrade strength and soil classification (22)



(A) MIDWAY BETWEEN DUAL TIRES

(B) DIRECTLY BENEATH ONE TIRE

1 lb_f = 4.448 N

Figure 10. Location of maximum horizontal tensile and vertical compressive subgrade strains in pavement structure (22).

summation of cycle ratios, which in simple form may be stated as

$$\sum_{i=1}^{i} \frac{n_i}{N_i} = D$$

where n_i = number of load applications at strain level i

N_i = number of load applications to cause failure in simple loading at strain level i

D = total cumulative damage

In this relationship, failure occurs when D equals or exceeds 1.0. Thus the design procedure becomes one of checking the particular pavement section to see that D is equal to or less than unity for the anticipated design conditions. When the value of D is considerably less than 1.0, the section may be underdesigned; when D is greater than 1.0, a redesign or reanalysis may be in order.

This relationship shows that a pavement section can fail due to fatigue after a particular number of load repetitions. Each of these load repetitions leading to failure can be associated with some strain or stress values whose magnitude will depend on the material. To date, it is somewhat difficult to specify allowable values of stress or strain to prevent fatigue, since these data are not as yet readily available from experience. However, for stabilized materials, one can use the values on Table 5 as guidelines for cumulative damage analysis.

Data from various laboratory studies can also be utilized directly. For example, fatigue relationships for cement-bound materials are shown in Volume I, Chapter V (Figure 31) as a function of applied stress to the ultimate stress. A similar relationship exists for lime-fly ash mixtures as seen in Volume I, Chapter IV (Figure 18). Typical fatigue relationships for asphalt-bound materials are included in Volume I, Chapter VI (Figures 34 and 35).

It should be noted that there exists a difference between laboratory and field fatigue response of pavements. Laboratory derived data, although reasonably accurate, and with correct slopes of the fatigue curves (such as shown in Volume I, Figure 34), may be offset from actual field data. All the evidence is not in, but it appears that if fatigue curves for laboratory and field conditions were plotted together, the laboratory curves would show about an order of magnitude (factor of 10) less fatigue life than the field. In other words, laboratory data are more conservative.

Multi-Layer Computer Programs

There are several computer programs currently available for performing elastic layered theory calculations. These include CHEV5L (Chevron Research Co.), BISTRO and BISAR (Shell Oil Co.), ELSYM5 (University of California, Berkeley), and CRANLAY (Australian Commonwealth Scientific and Industrial Research Organization) programs. All the programs have the capacity of solving for stresses, strains, and displacements for n-layer systems.

The basic input data to these programs consist of:

1. Wheel load data described by the total vertical load in pounds and tire pressure in psi,
2. Material properties of each layer characterized by the modulus of elasticity and Poisson's ratio, and
3. The thickness of each layer.

Also considered input are the locations at which calculations are requested.

For Some of these programs (e.g., CHEV5L and CHEV5L with iteration), output is given for only one circular load. Unfortunately, most vehicles for which pavements are to be designed have either dual or dual-tandem

Table 5. Approximate Fatigue Relationships for Stabilized Materials.

MATERIAL	NUMBER OF REPETITIONS TO FAILURE					
	10	100	1,000	10,000	100,000	1,000,000
Asphalt stabilized: tensile strain x 10^6 (dense graded)	4,000	2,000	850	400	140	85
Cement stabilized: tensile stress, psi (granular soil)	140	125	150	90	72	51
Cement stabilized: tensile stress, psi (silty clay)	92	85	78	70	62	54
Lime stabilized: ratio of applied stress to static strength**		0.81	0.75	0.69	0.63	0.57
Lime-fly ash stabilized ratio of applied stress to static strength*	.91	.82	.72	.63	.54	.46

*NCHRP Synthesis of Highway Practice #37, Lime-Fly Ash Stabilized Base and Subbases (R-1)

**M. R. Thompson, personal communication

1 psi = 6.89 x 10^3 Pa

configurations. The question arises, therefore, of how one determines the critical stresses, strains, or deformation for realistic wheel load configurations. This has been answered by using the principle of superposition. Using CHEV5L, one must do this manually, but ELSYM5 does it directly.

Layered elastic theory programs have enabled pavement engineers to place some emphasis on the more mechanistic design approach which allows extrapolation to any set of design conditions. This is particularly important because of the ever-increasing wheel loads such as those of off-highway vehicles. Layered theory programs use actual load data and fundamental material properties and can properly account for rapidly changing design conditions. In addition, evaluation of stabilized bases and subbases can be made even though little prior experience or performance data are available.

Other Elastic Layer Design Approaches

The general approach described above has evolved essentially from the procedure developed by Shell (20) in the early 1960's. That work and the new method (21) have become well recognized throughout the world; a summary appears below. A later approach developed by Chevron (22) has aimed not only at traditional asphalt concrete pavements, but also includes design curves for emulsified asphalt mixtures as well as cement-modified emulsified asphalt.

Shell Method

This method of pavement design has been developed for highway pavements (30, 31, 32, 33, 34) and later adapted to airfield pavement design (35). The method is applicable to situations with asphalt concrete resting on granular material and in turn on subgrade soils whose strength index can be defined by the CBR procedure (either by measurement or estimation). In addition, the procedure can be used for selecting the thickness of asphalt pavements resting directly on subgrade soils. Although not a part of the original design procedure, the use of the substitution-ratio concept would permit the inclusion of stabilized materials.

Principal design considerations. The pavement structure is represented by a three-layer elastic system (full friction at interfaces of layers) and the critical conditions for design are:

1. Horizontal tensile radial strain on the underside of the asphalt-bound layer; if excessive, cracking may occur on the asphalt layer, and

2. Vertical compressive strain in the surface of the subgrade; if excessive, permanent deformation may occur at the top of the subgrade, leading, in turn, to permanent deformation at the surface of the pavement.

An 18,000-lb (80 kN) single-axle load (9,000-lb (40 kN) wheel load) was used as the basis for design charts distributed in the United States. Because of limitations in computer solutions for multi-layer elastic systems at the time the procedure was developed (1962), subgrade strains were determined for a load applied to a single circular area with a radius of 6 inches (150 mm) and a contact pressure of 80 psi (550 kPa); tensile strains were, on the other hand, determined using a circular area with a radius of 4.2 inches (105 mm) and a contact pressure of 80 psi (550 kPa) (equivalent to 4,500 lb (20 kN) on one wheel of dual tires). Repetitions of the 18,000-lb (80 kN) axle load are considered as a part of the design process and the allowable strains associated with various numbers of repetitions are shown in Tables 6 and 7.

Table 6. Allowable Tensile Strain in Asphalt-Bound Layer Corresponding to Different Load Applications (30)

WEIGHTED LOAD APPLICATIONS	TENSILE STRAIN IN. PER IN.
10^5	2.3×10^{-4}
10^6	1.45×10^{-4}
10^7	9.2×10^{-5}
10^8	5.8×10^{-5}

1 in. = 2.54×10^{-2} m

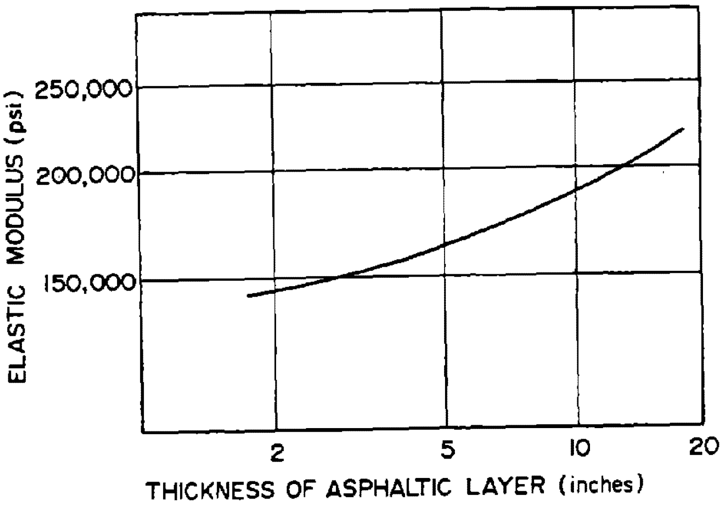
Table 7. Allowable Subgrade Compressive Strain Values Corresponding to Different Load Applications (30)

WEIGHTED LOAD APPLICATIONS	COMPRESSIVE STRAIN ON SUBGRADE IN. PER IN.
10^5	1.05×10^{-3}
10^6	6.5×10^{-4}
10^7	4.2×10^{-4}
10^8	2.6×10^{-4}

1 in. = 2.54×10^{-2} m

Material Properties. Materials in each of the three layers are assumed to be homogeneous, isotropic, and elastic.

Asphalt concrete. The time-of-loading and temperature dependency of asphalt concrete are included as key factors. Tensile strains in the asphalt concrete are determined for an assumed stiffness in this layer of 900,000 psi (6,200,000 kPa) (corresponds to a temperature of 50°F (10°C) and a time of loading of 0.02 sec.). For determination of subgrade strain, the air temperature is assumed to be 95°F (35°C), and effective stiffness modulus (depending on the thickness of asphalt concrete) is selected from Figure 11.



1 psi = 6.89 x 10^3 Pa   1 in. = 2.54 x 10^{-2} mm

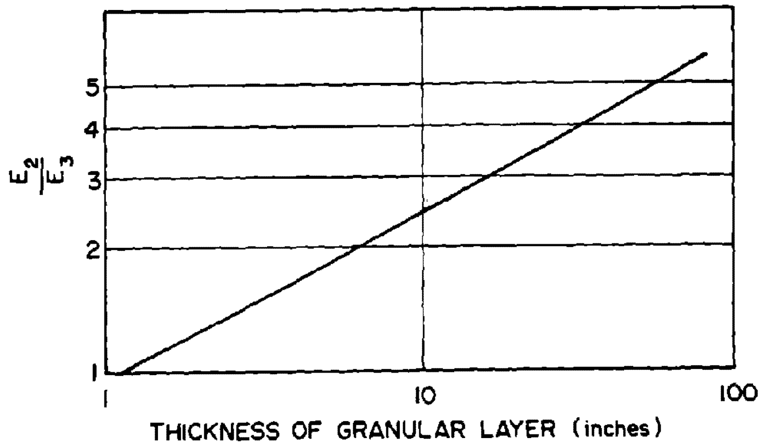
Figure 11. Relation of asphalt layer modulus to thickness of layer (air temperature of 95°F (35°C)) (33).

Untreated aggregate base. The modulus of the granular base is expressed in terms of the subgrade modulus and is dependent on the thickness of the base layer, Figure 12.

Subgrade soil. From dynamic (vibratory) tests in-situ, an appexoimate relationship between subgrade modulus (E_3) and CBR was established (31):

$$E_3 \text{ (psi)} = 1500 \cdot \text{CBR}$$

Since the computations were developed in the early 1960's at a time when solutions were available only for a Poisoon's ratio of 0.5 in each of the three layers, the design charts are based on this value for all the materials.



1 in. = 2.54×10^{-2} mm

Figure 12. Relation of modular ratio to granular base thickness (33).

Materials tests. In this procedure the only test potentially required is a CBR test on the subgrade soil to permit estimation of the modulus from the equation E = 1500 CGR (psi).

Typical design relationship. Design curves for a range in subgrade moduli are shown in Figure 13 for 10^6 repetitions of an 18,000-lb (80 kN) axle load. In this procedure, the design process simply consists of selecting a combination of thicknesses of asphalt concrete and untreated granular material from the appropriate relationship.

Thick-lift asphalt concrete sections. From curves such as those shown in Figure 13, it is possible to select, for a specific subgrade modulus, thicknesses of asphalt concrete corresponding to a thickness of the granular layer equal to zero. Alternatively, Heukelom and Klomp (34) have formulated a relationship developed from the design chart which is plotted in Figure 14 and has the form

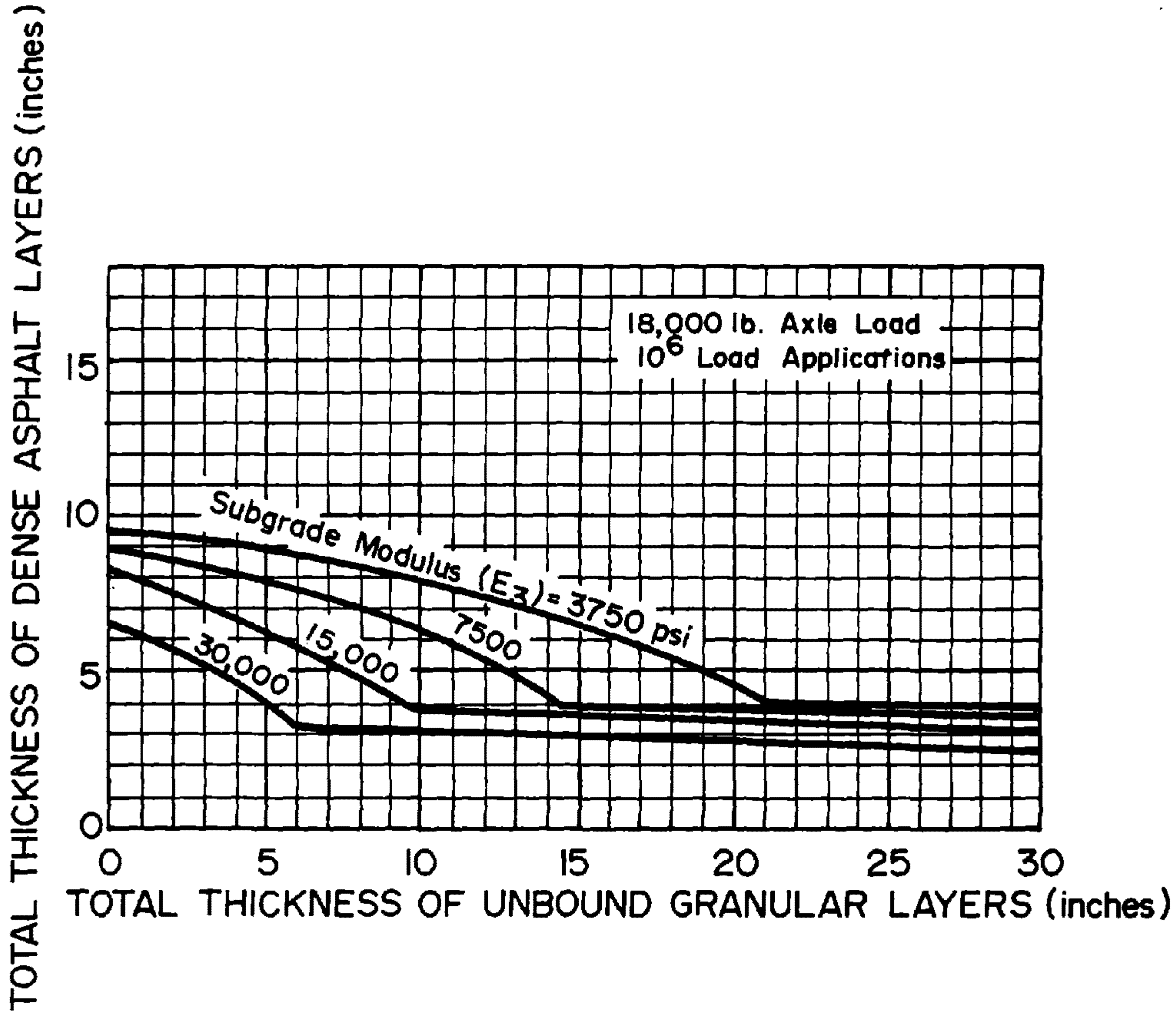
$$h = 10\ (2/3 \log N - \log E_s) + 13$$

where h = thickness of asphalt-bound layer, cm ($h > 6$ cm),

N = number of repetitions of axle load, and

E_s = subgrade modulus, kg per sq cm (E_3 in previous section).

Use with cement-stabilized layers. Like the other design procedures, a substitution ratio could be utilized with a value for stabilized material being selected from available data.



1 in. = 2.54×10^{-2} m
1 psi = 6.89×10^{3} Pa

Figure 13. Design curves for 10^6 load applications (21).

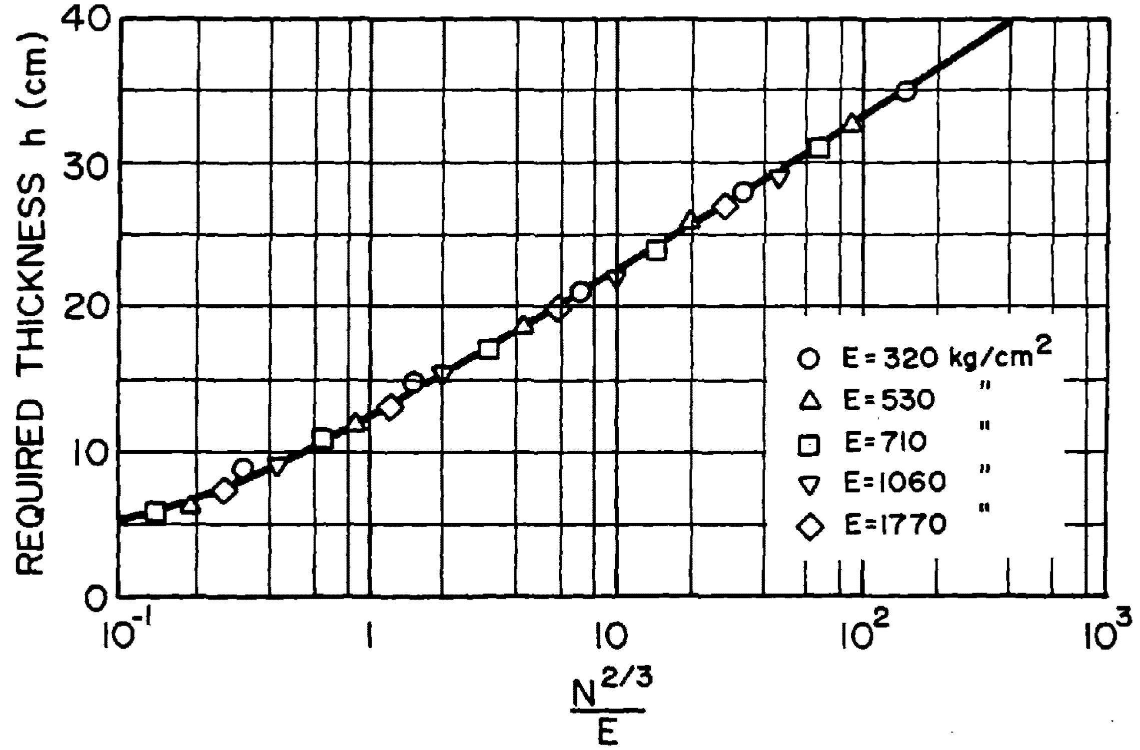


Figure 14. Design of thickness, h, of asphalt concrete layer resting directly on the subgrade as a function of the design number, N, and the subgrade modulus, E (34).

Chevron Method

The Chevron Research Company has developed a thickness design procedure (22) for pavement structures constructed with asphalt concrete, dense-graded emulsified asphalt mixes, or cement-modified emulsified asphalt mixes. Although this procedure has only recently been developed and has not had the use of the two methods described previously, it has a number of desirable features that provide it with the potential for more effective use of asphalt and emulsified asphalt stabilized materials.

Two critical strains, estimated by elastic layer theory, are examined in determinining proper pavement thickness. These are the horizontal tensile strain, ε_t, at the bottom of the treated layer and the vertical compressive strain, ε_v, at the surface of the subgrade (Figure 10).

Two locations are checked for the critical strains under a standard 9000 lb (40 kN) wheel load (18,000 (80 kN) lb axle load) on dual tires used for design--one midway between the wheels and the other directly under one of the wheels.

Allowable values for horizontal tensile strain are based on fatigue data developed from laboratory tests on asphalt concrete, emulsified asphalt, and cement-modified emulsified asphalt mixes. Vertical strain criteria for the subgrade have been selected to minimize surface rutting caused by overstressing the subgrade.

The steps in the design procedure are illustrated by the flow diagram of Figure 15 and Table 8 and will be summarized in the following sections.

Traffic. The mixed traffic is reduced to the number of daily equivalent 18,000 lb (80 kN) single-axle load (W_{18}) expected on the design lane during the selected design life of the structure (19, 36). The total traffic in equivalent 18,000 lb (80 kN) single-axle load (EAL) is determined from:

$$\text{EAL} = W_{18} \times 365 \times n$$

where n = design life in years.

Material Characteristics. The subgrade modulus, or stiffness, can be determined from repeated load triaxial compression tests (37), estimated from conventional tests [e.g., E (psi) = 1500 CBR (30)] or predicted from a soil classification (36). Poisson's ratio is assumed to be 0.45.

The modulus of asphalt or emulsified asphalt mixes is determined with the recently developed diametral resilient modulus (M_R) device (38). For this simplified thickness design procedure, M_R is measured at 73° ± 3°F (23° ± 1.7°C) on a fully cured specimen. A 5:1 ratio of M_R at 73°F (23°C) to M_R at 100°F (38°C) is assumed for all mixes.

It is also necessary to determine the air void and asphalt contents of the design mix. These properties have been shown to significantly influence the fatigue performance of an asphalt mix (39, 40), and, hence, the thickness requirements for the pavement. The ratio of asphalt volume to air voids plus asphalt volume is used as an indicator of the relative fatigue behavior of the mix.

Effect of Early Cure of Emulsified Asphalt Mixes. The time for an emulsified asphalt mix to reach its final M_R in the field is also important in determining its design thickness. Based in part on Chevron's field experience with emulsified asphalt mixes, the evapotranspiration map shown in Figure 16 has been selected as a guide for estimating cure periods of emulsified asphalt mixes. Emulsified asphalt mixes placed in parts of the southwest and most of Texas and Florida are expected to reach their ultimate design modulus in six months. A two-year cure period is assumed for emulsified asphalt mixes

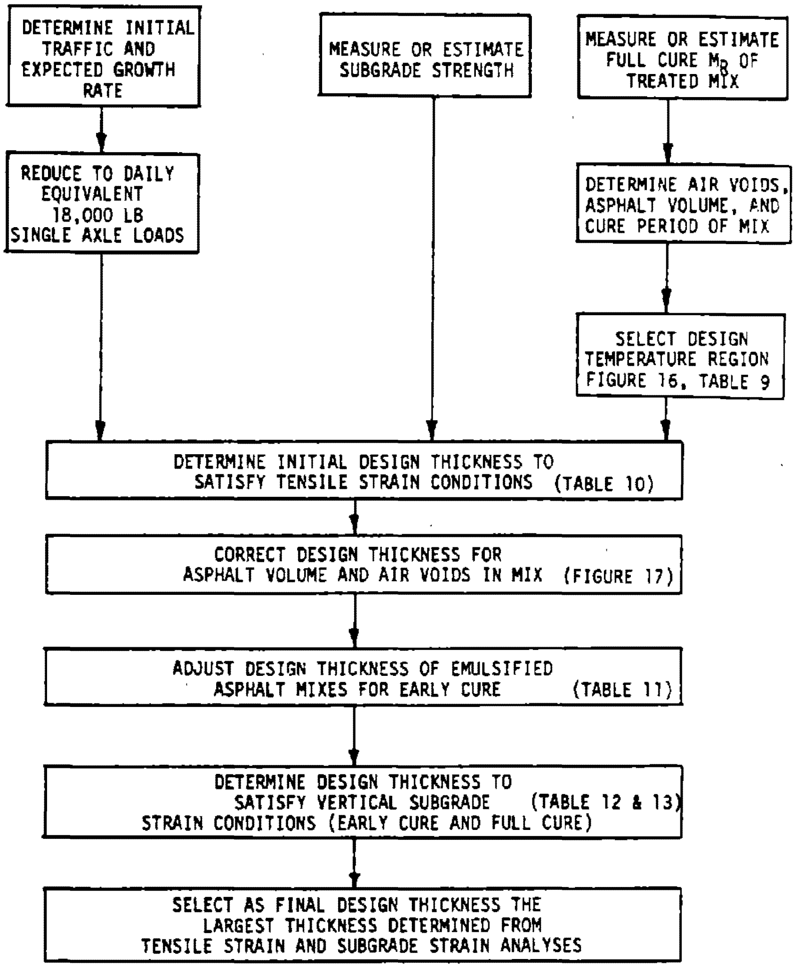


Figure 15. Flow diagram for structural design or emulsified asphalt pavement.

Table 8. Design Summary Sheet (22)

Subgrade Modulus, E_s, psi = 12,000
Design Life, n, Years = 20
Traffic, W_{18} = 137
Traffic, EAL = 1,000,000
Temperature Region, AAAT, °F = 55-65

	ASPHALT MIX	EMULSIFIED ASPHALT MIX
Modulus, M_R (73°F), psi	300,000	600,000
Air Voids, V_a, %	5	10
Asphalt Volume, V_b, %	12	9
Cure Period, Months	--	12
Tensile Strain Evaluation		
Design Thickness, T_t, in.	8.1	10.6
Subgrade Strain Evaluation		
Design Thickness (Early Cure), T_s, in.	--	7.8
Design Thickness (Full Cure), T_s, in.	8.3	8.3
Final Pavement Design		
Thickness, T_A, in.	8.3	10.6

1 psi = 6.89×10^3 Pa
1 in. = 2.54×10^{-2} m
°C = 5/9 (°F - 32)

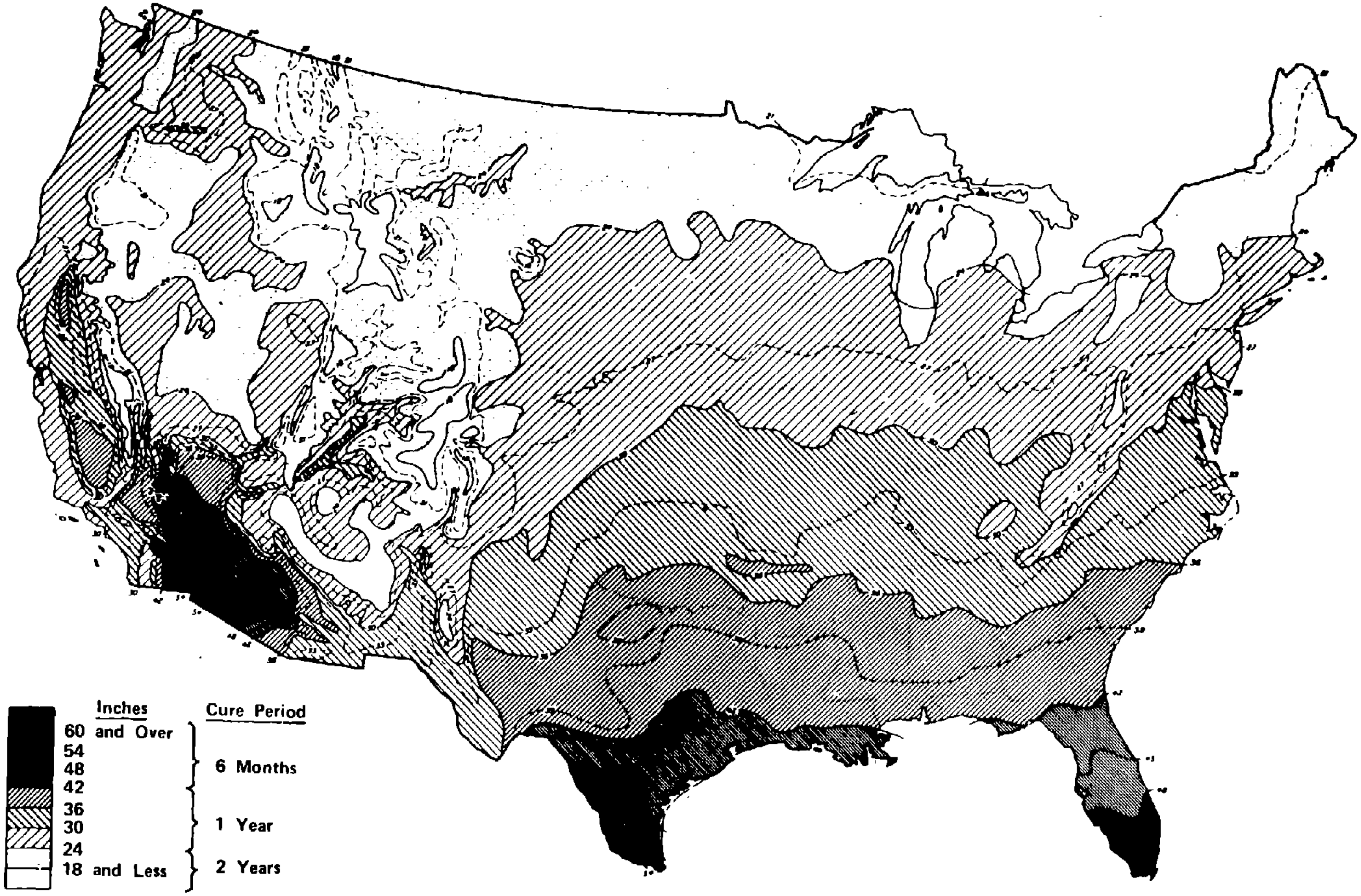


Figure 16. Field cure periods for emulsion treated mixes based on annual potential evapotranspiration map (22).

placed in the northern regions of the map.

Effect of Temperature. Temperature has a significant influence on the thickness design of an asphalt or emulsified asphalt pavement through its effect on mix modulus. The effect of temperature is taken into account by designing for four different temperature regions. These are identified by average annual air temperatures (AAAT) of <40°F, 40-55°F, 55-65°F, and >65°F (<4, 4-13, 13-18, and >18°C). A partial listing of communities falling into these temperature regions is given in Table 9. The communities of Juneau, Alaska (<40°F (<4°C));

Table 9. Temperature regions used in thickness design (22).

AVERAGE ANNUAL AIR TEMPERATURE, °F			
<40	40-55	55-65	>65
Anchorage Fairbanks Juneau Nome	Flagstaff Denver Portland, Me. Minneapolis Reno Albany Fargo Spokane Eureka Chicago Boston Detroit Portland, Or. Salt Lake City Boise Omaha	Washington, D.C. Louisville Oklahoma City Richmond, Va. Mobile Sacramento San Diego Atlanta	Phoenix Miami Hilo Corpus Christi Bakersfield New Orleans Las Vegas Dallas

$°C = \frac{5}{9} (°F - 32)$

Portland, Oregon (40-55°F (4-13°C)); Sacramento, California (55-65°F (13-18°C)); and Bakersfield, California (>65°F (>18°C)) were selected as being representative of the specific temperature regions and are used to develop the design tables included in this manual. The selection of other communities from the appropriate temperature regions will produce approximately the same thickness requirements.

Structural Design. With the above data, a pavement thickness is selected to ensure that the horizontal tensile strain on the underside of the asphalt or emulsified asphalt-treated layer and the vertical strain at the subgrade surface satisfy the established criteria.

A design summary sheet, like that shown in Table 8, can be used to determine the final design thickness of a pavement structure. A minimum full-depth design thickness of 4 inches (100 mm) is recommended. The following steps are taken in the design:

Tensile Strain Evaluation

1. Determine the initial design thickness, T_i, from Table 10. For values of subgrade modulus and mix modulus, M_R, other than those given in Table 10, T_i can be estimated by interpolation or extrapolation. Thicknesses of 2 inches (50 mm) and 24 inches (600 mm) have been established as practical lower and upper limits.

2. Correct T_i for the volume of air voids and asphalt residue in the design mix using the variable

$$\frac{V_b}{V_a + V_b}$$

where V_b = volume of asphalt residue, %

V_a = volume of air voids, %

The nomograph in Figure 17 can be used to make this correction. The volume of asphalt residue, V_b, in the above expression is obtained from

$$V_b = \frac{P_b G_s (100 - V_a)}{100 \times G_b + P_b \times G_s}$$

where P_b = % by weight of asphalt residue (based on dry weight of aggregate)

B_b = specific asphalt

Table 10. Thickness*, T_i, in inches to satisfy tensile strain requirements (22).

SUBGRADE MODULUS, PSI	3,000				6,000				12,000				30,000			
AVERAGE ANNUAL AIR TEMPERATURE, °F	< 40	40-55	55-65	> 65	< 40	40-55	55-65	> 65	< 40	40-55	55-65	> 65	< 40	40-55	55-65	> 65
Traffic, EAL = 10^4																
M_R, psi = 50,000	4.9	6.5	7.8	9.1	3.7	5.0	5.8	6.6	2	2.6	2.8	2.9	2	2	2	2
100,000	3.7	5.3	6.2	7.2	2.7	4.0	4.7	5.3	2	2.1	2.5	2.6	2	2	2	2
300,000	2.1	3.4	4.3	5.1	2	2.8	3.1	3.8	2	2	2	2	2	2	2	2
600,000	2	2.4	3.2	3.9	2	2	2.2	2.8	2	2	2	2	2	2	2	2
900,000	2	2	2.6	3.3	2	2	2	2.2	2	2	2	2	2	2	2	2
Traffic, EAL = 10^5																
M_R, psi = 50,000	8.3	11.5	13.9	16.5	7.0	9.7	11.2	12.7	5.4	7.3	8.3	9.3	2.3	2.7	2.8	2.9
100,000	6.3	9.0	10.8	12.9	5.4	7.6	9.1	10.5	4.2	5.8	6.9	7.8	2	2.5	2.7	2.7
300,000	4.0	5.8	7.3	8.7	3.3	5.1	6.0	7.3	2.4	3.9	4.8	5.6	2	2	2.0	2.2
600,000	2.8	4.5	5.5	6.7	2.1	3.7	4.7	5.6	2	2.7	3.6	4.4	2	2	2	2
900,000	2.1	3.7	4.7	5.7	2	3.0	3.9	4.8	2	2.1	2.9	3.7	2	2	2	2
Traffic, EAL = 10^6																
M_R, psi = 50,000	13.0	18.1	21.6	24	11.6	16.1	18.7	21.3	9.8	13.1	15.1	17.2	6.8	8.6	9.3	9.8
100,000	9.8	14.3	17.1	20.3	8.8	12.6	15.2	17.6	7.5	10.6	12.5	14.2	5.2	7.3	8.2	8.7
300,000	6.0	9.1	11.3	13.9	5.5	8.2	10.1	12.2	4.7	6.9	8.6	10.2	3.1	4.9	5.9	6.9
600,000	4.6	6.8	8.6	10.6	4.0	6.0	7.6	9.4	3.3	5.2	6.4	7.9	2	3.5	4.5	5.4
900,00	3.7	5.6	7.2	8.9	3.2	5.1	6.3	8.0	2.4	4.3	5.4	6.7	2	2.8	3.8	4.6
Traffic, EAL = 10^7																
M_R, psi = 50,000	19.2	24	24	24	17.8	23.9	24	24	15.6	20.5	23.5	24	12.1	15.3	16.5	17.3
100,000	14.5	21.0	24	24	13.5	19.3	22.8	24	11.9	16.8	19.5	22.2	9.5	12.9	14.7	15.7
300,000	8.8	13.6	16.7	20.5	8.3	12.5	15.6	18.8	7.4	11.1	13.8	16.4	5.8	8.8	10.8	12.4
600,000	6.4	10.0	12.5	15.6	5.9	9.2	11.6	14.5	5.3	8.2	10.4	12.8	4.1	6.5	8.2	10.0
900,000	5.3	8.2	10.5	13.2	5.0	7.7	9.7	12.1	4.4	6.8	8.6	10.8	3.3	5.3	6.8	8.5

*For asphalt volume, V_b = 11% and air voids, V_a = 5%. Use Figure 17 to correct for other values of V_a and V_b.

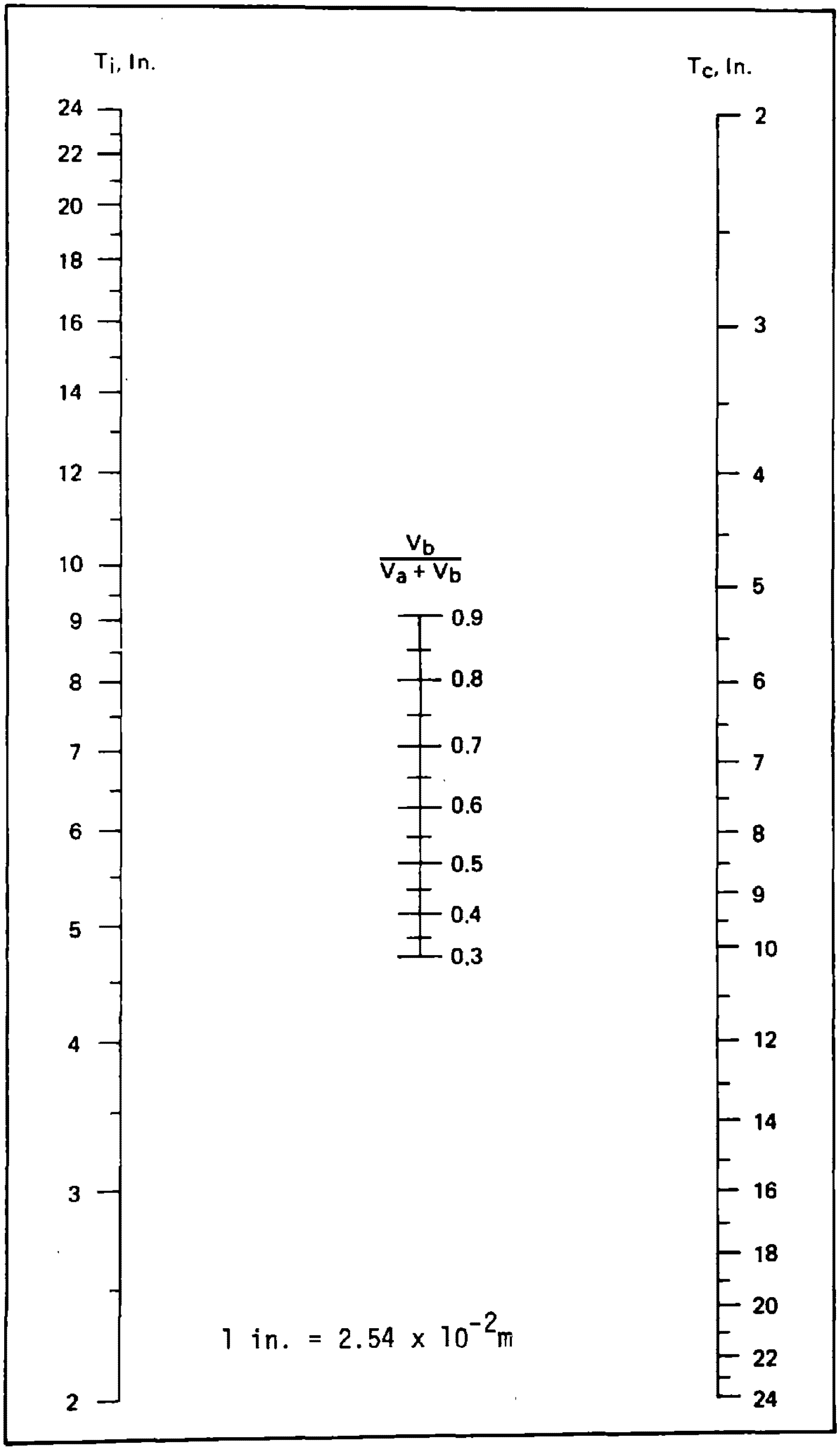


Figure 17. Correction of pavement design thickness for air voids and asphalt content in mix (22).

G_s = average specific gravity of aggregate

3. In the case of emulsified asphalt mixes, multiply the thickness determined in Step 2 by the appropriate early cure adjustment factor in Table 11.*

   The addition of a small amount of portland cement** will significantly increase the early strength (modulus) of emulsified asphalt mixes. The use of cement-modified emulsified asphalt mixes eliminates the need for an early cure adjustment to the design thickness.

4. Record as the design thickness from tensile strain evaluation, T_t, the value determined from Step 2 or 3.

Table 11. Correction Factor for Early Cure Period of Emulsified Asphalt Mixes (22)

CURE PERIOD, MONTHS	DESIGN LIFE, YEARS	
	10	20
6	1.05	1.03
12	1.06	1.03
24	1.15	1.08

Subgrade strain Evaluation

5. With emulsified asphalt mixes, examine the early cure condition for subgrade strain using Table 12.*

---

*This step is eliminated for asphalt mixes and cement-mofieidl emulsified asphalt mixes.

**The cement content is normally between 1% and 2% by weight of dry aggregate. For a satisfactory fatigue life, the ratio of cement to emulsified asphalt in the mix should not be more than one part cement to five parts emulsified asphalt by weight (see Volume 2, Chapter VII on Combination Stabilizers).

Table 12. Thickness, T_s, in inches to satisfy subgrade strain requirements (early cure condition)[1]

SUBGRADE MODULUS, PSI	3,000				6,000				12,000				30,000			
Average Annual Air Temperature, °F	<40	40-55	55-65	> 65	<40	40-55	55-65	> 65	<40	40-55	55-65	>65	<40	40-55	55-65	>65
Traffic, EAL = 10^2	3.0	7.6	8.7	9.2	2.9	5.4	6.1	6.4	2.6	3.0	3.1	3.1	2.5	2.9	3.0	3.0
Traffic, EAL = 5 x 10^2	5.2	9.2	11.0	11.9	4.4	6.9	7.8	8.2	2.8	4.5	4.9	5.1	2.7	3.1	3.2	3.2
Traffic, EAL = 10^3	6.1	9.9	12.0	13.0	5.0	7.5	8.5	9.0	2.9	5.1	5.7	6.0	2.8	3.2	3.3	3.3
Traffic, EAL = 5 x 10^3	8.1	13.0	15.3	16.4	6.8	10.2	11.6	12.3	4.8	7.3	8.2	8.6	3.1	3.9	4.2	4.4
Traffic, EAL = 10^4	9.0	14.4	16.7	17.9	7.5	11.4	12.9	13.7	5.7	8.3	9.2	9.7	3.2	4.2	4.6	4.8

[1] Early cure period is taken as the most critical first month (normally July) after construction. Mix modulus during this period is assumed to be 50,000 psi at 73°F.

1 in. = 2.54 x 10^{-2}m
1 psi = 6.89 x 10^3 Pa
°C = 5/9 (°F-32)

Table 13. Thickness, T_s, in inches to satisfy subgrade strain requirements (fully cured condition)

SUBGRADE MODULUS, PSI	3,000				6,000				12,000				30,000			
AVERAGE ANNUAL AIR TEMPERATURE, °F	< 40	40-55	55-65	> 65	< 40	40-55	55-65	> 65	< 40	40-55	55-65	> 65	< 40	40-55	55-65	> 65
Traffic, EAL = 10^4																
M_R, psi = 50,000	5.5	8.3	10.8	11.5	4.6	7.0	8.3	9.3	3.0	5.4	6.2	6.9	2.5	3.1	3.3	3.5
100,000	5.5	6.0	7.3	8.2	4.6	5.0	6.1	7.0	3.0	3.4	4.6	5.3	2.5	2.5	2.9	3.0
300,000	5.5	5.5	5.5	5.5	4.6	4.6	4.6	4.6	3.0	3.0	3.0	3.0	2.5	2.5	2.5	2.5
600,000	5.5	5.5	5.5	5.5	4.6	4.6	4.6	4.6	3.0	3.0	3.0	3.0	2.5	2.5	2.5	2.5
900,000	5.5	5.5	5.5	5.5	4.6	4.6	4.6	4.6	3.0	3.0	3.0	3.0	2.5	2.5	2.5	2.5
Traffic, EAL = 10^5																
M_R, psi = 50,000	8.1	12.7	14.5	16.5	6.9	10.3	12.4	13.9	5.5	8.3	9.5	10.6	2.9	5.2	6.1	6.7
100,000	8.1	8.7	10.6	12.0	6.9	7.4	9.1	10.2	5.5	6.0	7.2	8.2	2.9	3.0	4.7	5.2
300,000	8.1	8.1	8.1	8.1	6.9	6.9	6.9	6.9	5.5	5.5	5.5	5.5	2.9	2.9	2.9	2.9
600,000	8.1	8.1	8.1	8.1	6.9	6.9	6.9	6.9	5.5	5.5	5.5	5.5	2.9	2.9	2.9	2.9
900,000	8.1	8.1	8.1	8.1	6.9	6.9	6.9	6.9	5.5	5.5	5.5	5.5	2.9	2.9	2.9	2.9
Traffic, EAL = 10^6																
M_R, psi = 50,000	11.5	16.8	20.1	22.4	9.8	15.0	17.3	19.3	8.3	12.2	14.4	15.8	6.0	8.6	9.5	10.4
100,000	11.5	12.3	14.8	16.5	9.8	10.8	13.0	14.7	8.3	9.0	10.8	12.1	6.0	6.6	7.6	8.5
300,000	11.5	11.5	11.5	11.5	9.8	9.8	9.8	9.8	8.3	8.3	8.3	8.3	6.0	6.0	6.0	6.0
600,000	11.5	11.5	11.5	11.5	9.8	9.8	9.8	9.8	8.3	8.3	8.3	8.3	6.0	6.0	6.0	6.0
900,000	11.5	11.5	11.5	11.5	9.8	9.8	9.8	9.8	8.3	8.3	8.3	8.3	6.0	6.0	6.0	6.0
Traffic, EAL = 10^7																
M_R, psi = 50,000	15.5	22.6	24	24	13.6	20.4	23.9	24	12.0	17.5	20.6	22.6	9.0	12.7	14.3	15.4
100,000	15.5	16.5	19.9	22.2	13.6	15.0	17.9	19.9	12.0	13.0	15.5	17.2	9.0	9.8	11.2	12.6
300,000	15.5	15.5	15.5	15.5	13.6	13.6	13.6	13.6	12.0	12.0	12.0	12.0	9.0	9.0	9.0	9.0
600,000	15.5	15.5	15.5	15.5	13.6	13.6	13.6	13.6	12.0	12.0	12.0	12.0	9.0	9.0	9.0	9.0
900,000	15.5	15.5	15.5	15.5	13.6	13.6	13.6	13.6	12.0	12.0	12.0	12.0	9.0	9.0	9.0	9.0

1 psi = 6.89×10^3 Pa
1 in. = 2.54×10^{-2} m
°C = 5/9 (°F-32)

   a. Calculate traffic for critical period (normally first month after construction).

   b. For the appropriate subgrade modulus and temperature region, estimate the required design thickness, T_S.

6. Examine the fully cured condition for subgrade strain using Table 13.

   a. Calculate traffic during the fully cured period.*

   b. For the appropriate subgrade modulus, M_R, and temperature region, estimate the required design thickness, T_S.

7. Record as the design thickness from subgrade strain evaluation, T_S, the larger of the values determined from Step 5 or Step 6.

8. Record as the final pavement thickness, T_A, the larger of the design thicknesses from Step 4 or Step 7.

Composite Pavement Structures

9. For composite pavement structures, determine the final design thickness for each mix under consideration. Calculate thickness substitution ratios and use to recommend composite structure.

   For example, comparing an asphalt mix and emulsified asphalt mix, the full-depth design might be:

   T_A = 12 in. (305 mm) (emulsified asphalt mix)

   T_A = 9 in. (230 mm) (asphalt mix)

   The substitution ratio is 12/9 = 1.22. A recommended composite structure might be:

   Surface layer (asphalt mix) = 3 in. (76 mm)

   Base (emulsified asphalt mix) = (9-3) x 1.33**= 8 in. (203 mm)

---

*No early cure adjustment for traffic is necessary for asphalt mixes and cement-modified emulsified asphalt mixes.

**The ratio of 1.33 applies to this example only. Higher or lower values will be obtained for different design situations.

Discussion of Chevron Procedure

The fatigue criteria used in the tensile strain evaluation are for mixes with up to 12.5% air voids and an asphalt volume of 11%. Very little fatigue information exists on higher void content (lower $\frac{V_b}{V_a + V_b}$) mixes. Mixes with extremely high void contents (>20%) such as open-graded mixes seldom fail in the field by fatigue. It is conceivable that the primary thickness design consideration for these mixes is vertical subgrade strain. Permanent deformation of the mix itself is also an important design consideration for such materials.

Inspection of Table 10 shows that, for high temperature regions (AAAT >65°F (18°C)), relatively large design thicknesses are predicted with low stiffness mixes. This suggests that higher stiffness mixes (equal to or greater than 300,000 psi (2.070,000 kPa) are more appropriate for these regions. One way of obtaining higher stiffness is to use a harder asphalt. Conversely, in low temperature regions, the design thickness obtained from a tensile strain evaluation is normally less than that required from a subgrade strain evaluation for moderate-to-high stiffness mixes. This permits a reduction in the stiffness of the mix selected without necessarily increasing the final design thickness. The use of low stiffness mixes in cold climate areas will significantly improve the pavement's resistance to thermal cracking.

This design procedure also permits preliminary examination of the economics of pavement construction, taking into account the interrelationships between asphalt or emulsified asphalt mix characteristics and pavement thickness.

OTHER PAVEMENT DESIGN METHODS

Apart from the AASHO Interim Guide and Multilayered Elastic methods, there are several other pavement design methods available. In 1968 and 1969, the Highway Research Board Committee on Theory of Pavement Design conducted a review of all the existing theories and methods of pavement design (28). Two of the methods as summarized by the committee are included in this manual. These are

a. The State of California method for thickness Design of Asphaltic Concrete Pavements (38, 41, 42)

b. Asphalt Institute Method for the design of asphalt pavements (43, 44).

Other methods for flexible pavement design that are not included in this manual but may be helpful for stabilized layers are:

a. Kansas, Texas, Michigan, or Washington State method for design of flexible pavements

b. Canadian Department of Transportation Method for thickness design of flexible pavements.

California Method

This method was developed by Hveem in the 1940's and has been modified on the basis of data from road tests as well as from in-service highways in California. Pavement thickness in this empirical method is determined by the requirement that permanent deformation in each layer of the pavement system be prevented. The thickness desired to accomplish this is considered to be a function of the traffic, tensile properties of paving materials, and the shear strength characteristics of the paving materials as measured by the stabilometer tests.

This method is largely empirical, and therefore is based on the general assumption that the relationships developed apply under all conditions in which they will be used. In addition the following assumptions are made:

1. That the effect of traffic repetitions and vehicle weight can be expressed by a "Traffic Index" which is presumed to be a measure of the number of repetitions of a 5000-pound (22 kN) equivalent wheel load during the design life,

2. That the stabilometer tests can provide an appropriate measure of the strength characteristics of the paving materials for use in design, and

3. That there is an equivalency between various thicknesses of different materials in the pavement system. This equivalency is a function of the tensile properties of the material, and can be described in terms of an empirically-determined "gravel equivalent factor" which represents the thickness of a given material equivalent to a unit thickness of gravel subbase. This equivalency concept is very useful to accommodate stabilized layers for base and subbase.

The material properties used to select a pavement thickness by this method are:

1. "R"-value as measured by the stabilometer. Normally a particular material is prepared at a series of water contents and dry densities,

2. The exudation pressure. This is the pressure required to force water from a sample of the appropriate material which has been compacted in a mold by kneading methods,

3. Tensile strength of paving components as measured by the cohesiometer test and
4. Expansion pressure of subgrade materials.

This procedure has been used successfully by the California Division of Highways in a number of modified forms since the early 1940's and has been adopted by a number of other Western states.

Asphalt Institute Method

This method was developed from the statistical analysis of data from the AASHO Road Test. Information from the WASHO Road Test, from British Test Roads, older editions of the Asphalt Institute manual, and state highway and other existing design procedures were incorporated. The present version was published in 1963; however, a new manual is in preparation and will probably be published in 1979.

The adequacy of the structural design is measured by the change in the Present Serviceability Index (PSI) of the pavement. The PSI is defined as the momentary ability of the pavement to serve traffic. The change in PSI is a function of the number and rate of all axle and wheel loads, strength of the subgrade soil in its critical moisture condition, and strength or relative strengths, of the surface, base, and subbase courses. These terms were discussed under the AASHO method earlier in this chapter.

Several assumptions are required:

1. That the number of applications of various wheel loads can be expressed in terms of an equivalent number of 18,000 pound (80 kN) single-axle load applications. This assumption leads to the development of equivalence factors and the expression of traffic loadings in terms of a common denominator,
2. That the effect of one pavement material, i.e., asphaltic concrete or granular base course, relative to that of another material in the pavement system, is proportional to the ratio of their thicknesses. Thus the concept of equivalency of a thickness of one material to a different thickness of another material is assumed,
3. That the relationships found between the equivalent pavement thickness, the equivalent number of 18-lip (80 kN) axle loads, and the soil support value for the AASHO Road Test data are valid for all soil types and
4. That the soil support value can be measured by either the California Bearing Ratio (CBR) or the Stabilometer R-value.

Material Properties. The soil support value is determined by either the California Bearing Ratio test or the Stabilometer test. No determination of properties of the other pavement components is made. However, it is assumed that all such components exhibit at least the minimum quality specified in terms of gradation, CBR, Marshall stability, and other standard tests normally used in highway work.

SUBBASES FOR RIGID PAVEMENTS

The preceding discussion of pavement design has been directed to flexible pavements. The majority of stabilization for pavement structures is in conjunction with base and subbase courses for flexible pavements, but the engineer must also be able to provide for stabilized layers under portland cement concrete.

Design methods for concrete pavements include those developed by the Portland Cement Association (PCA) (45) as well as others. Many state agencies use the PCA method or variations of it. Subgrade and subbase materials must be assigned a strength value called the modulus of subgrade reaction, "k". The scales for k included in the design charts are correlated with values obtained by plate loading tests performed in accordance with AASHTO Designation T222 using a 30-inch diameter plate. The k value may be estimated on the basis of previous experience, or by correlation with other tests.

For example, the k value for a range of soil-conditions is shown in Figure 18 along with other test parameters for correlation purposes. Although these correlations may be somewhat general, they provide the engineer with a comparison to other familiar parameters and a place to start in lieu of actual field testing.

Correction of k Values for Stabilized Subbase

One should recognize that using stabilized bases under concrete pavements increases the k value. Three methods are available for correcting the k value:

1. Perform plate tests on top of the base; maximum k = 500 pci.
2. Correct the subgrade modulus using correlation charts (Figure 18).
3. Use the trial and error procedure in which the relative stiffness of the slab is corrected using the method developed by Packard (46).

For cement treated bases, PCA has developed a method of determining a "combined" k on the subgrade and subbase. Figure 18A shows two sets of curves for this purpose and is useful for estimating the k for various situations.

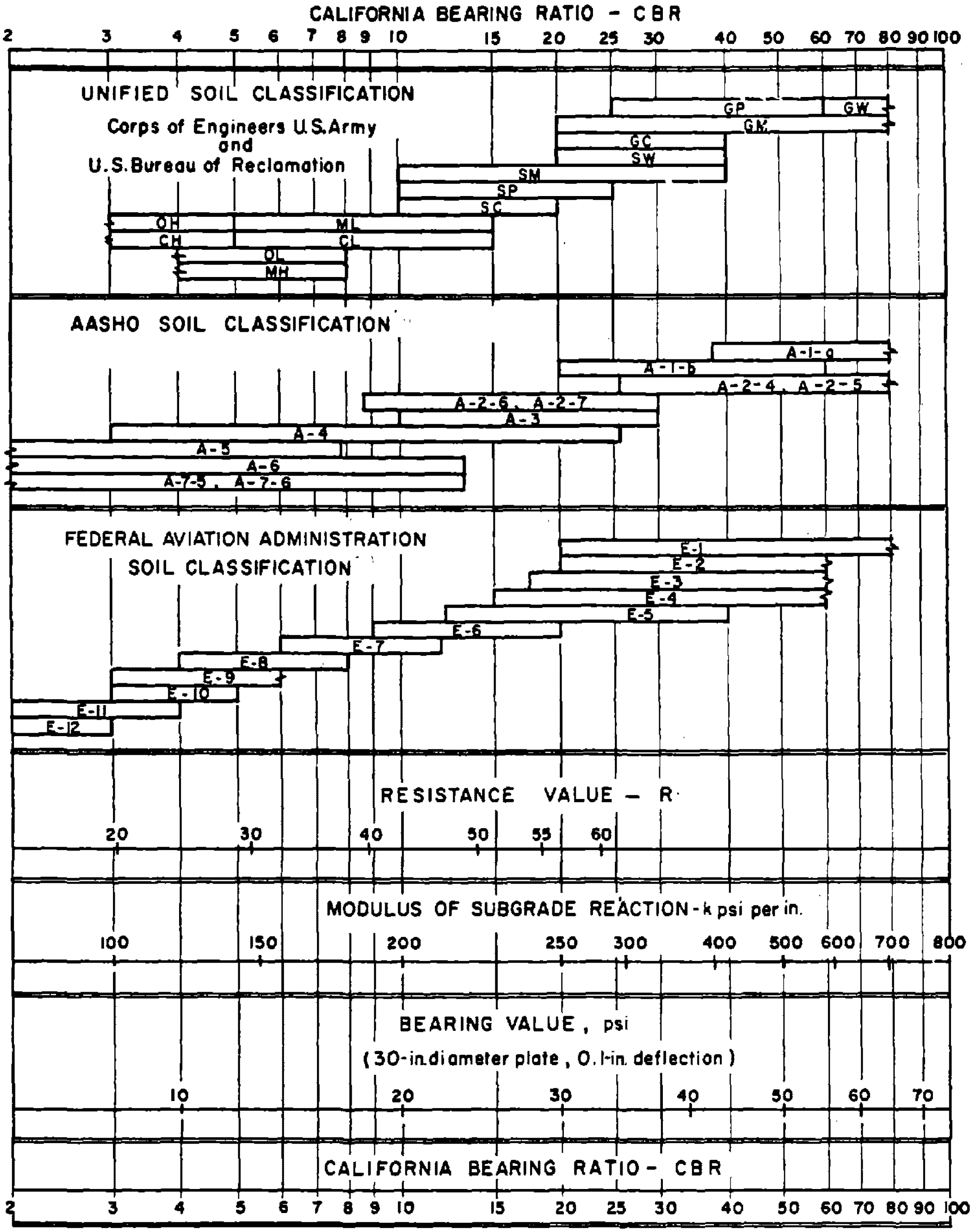
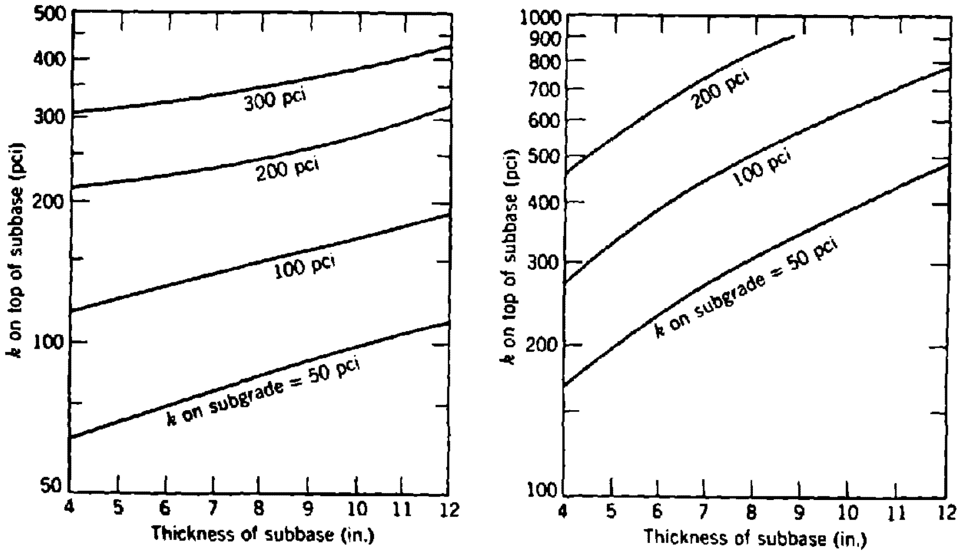


Figure 18. Approximate interrelationships of soil classifications and bearing values (45).



(a) (b)

Figure 18A. Effect of subbase thickness on modulus of subgrade reactions. (a) Untreated and (b) cement-treated (46).

Although data are scarce, it has been suggested that k values for asphalt and lime treated subbases are similar to those for cement treated bases, hence Figure 18 could be used for estimating.

MINIMUM LAYER THICKNESS

In order to prevent problems with construction and maintenance, impractical designs should be avoided. For example, it is generally impractical and uneconomical to place surface, base, or subbase courses of less than some minimum thickness. For purposes of this manual, the following are suggested:

	Cement treated	Lime treated	Asphalt treated
Surface course	-	-	1.5 inches
Base course	4 inches	4 inches	4 inches
Subbase course	4 inches	4 inches	4 inches

IV. CONSTRUCTION

INTRODUCTION

In the construction of stabilized soil systems the objective is to obtain a thorough mixture of a pulverized soil or aggregate material with the correct quantity of stabilizer and sufficient fluids to permit maximum compaction. Specifically, equipment must be selected, operated, and sequenced to provide the following:

1. The proper water content (uniformly mixed),
2. The proper stabilizer content (uniformly mixed),
3. The attainment of some minimum specified density,
4. Favorable temperature and moisture conditions for strength development during the curing period, and
5. Protection of the stabilized surface from traffic to prevent abrasion and to ensure adequate time for strength development.

Mixed-in-place construction methods using travelling mixing machines or central plant mixing operations can be utilized. The choice of the method will depend upon the local job conditions including equipment availability. If in-place soil material can be economically stabilized, the mixed-in-place method would probably be used. If the material is to be obtained from a borrow source and the project is of sufficient size, it may be economical to use central plant mixing techniques. Whatever the type of mixing equipment used, the general construction principles, procedures, and objectives are the same. Construction methods defined by the type of mixing (mixed-in-place or central plant) and shown in Figure 19 are briefly discussed below.

MIXED-IN-PLACE

Mixture uniformity for mixed-in-place operations is usually less than that obtained using central plant mixing operations; however, satisfactory results can be obtained with road mixing equipment for all of the major chemical stabilizers. Lime and cement subgrade stabilization utilizing mixed-in-place techniques is very popular in some parts of the United States. The major steps for mixed-in-place operations are:

1. Soil preparation,
2. Stabilizer applications,
3. Pulverization and mixing,

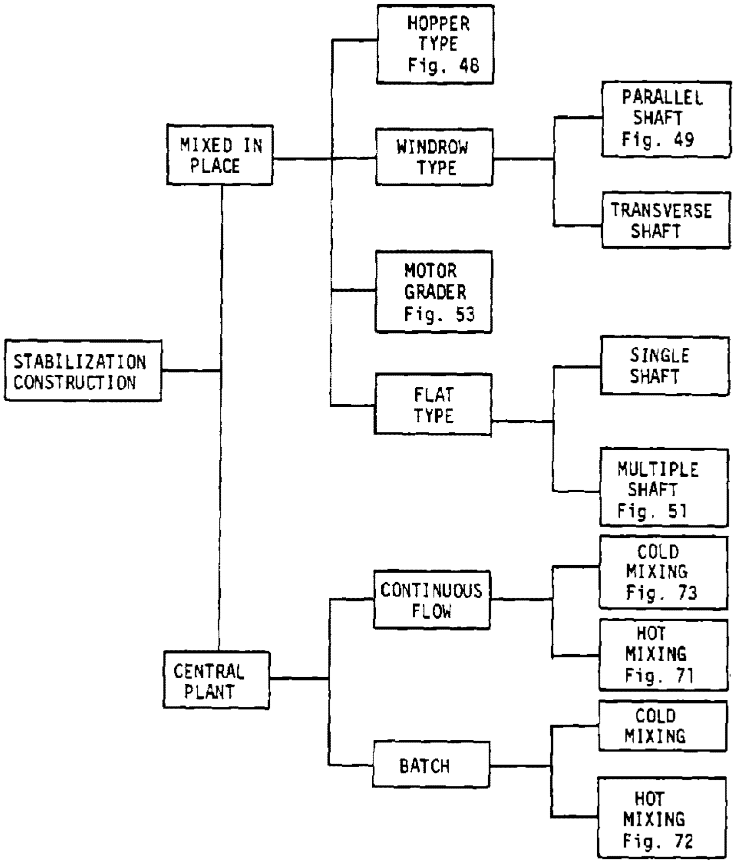


Figure 19. Soil stabilization construction equipment.

4. Compaction, and
5. Curing.

Excellent general summaries of these processes can be found in the literature. For example, lime stabilization construction operations are documented in references 47 and 48, lime-fly ash stabilization in references 49 and 50, cement stabilization in reference 51, and asphalt stabilization in reference 52. Mixed-in-place operations have been defined by these references as follows:

1. Mixing with the existing subgrade materials,
2. Mixing with a borrow source at the construction site and
3. Mixing with a borrow source at an off-pavement site and transporting to the pavement site.

Mixing operations with subgrade materials are often performed with single- and multiple-shaft flat type mixes or motor graders. Mixing with borrow materials is often performed with windrow type mixers or hopper type mixers if base course materials are to be produced. Photographs of mixing equipment are shown on Figures 20 to 25. A summary of mixed-in-place operations utilized for lime, cement, asphalt, and fly ash stabilization is given below. For discussion purposes, typical subgrade, subbase, and base course stabilization construction operations will be described. The subbase and base course stabilization operation will consist of borrow material mixed in a windrow because this is a common form of subbase and base course stabilization.

Subgrade Stabilization

The following construction steps are typically employed for subgrade stabilization operations:

1. Soil preparation,
2. Stabilizer application,
3. Pulverization and mixing,
4. Compaction and
5. Curing.

These operations are basic to the use of lime, cement, asphalt, and fly ash stabilization.

Soil Preparation. After the soil has been brought to the proper line and grade as shown on the construction plans, initial scarification and partial pulverization should be performed to the specified depth and width of stabilization. During and after scarification and pulverization, all deleterious materials like stumps, roots, turf, etc., and aggregates larger than 3 inches (76 mm) should be removed.

The grader-scarifier and/or disc harrow are commonly used for initial scarification, and the disc harrow and rotary mixer for pulverization (Figures 26 and 27). Plows, various types of cultivators, and other agricultural equipment can be used. When the soil is unusually dry, water is added to aid pulverization; if extremely wet, the rotary mixer or disc harrow can be used for aerating and drying the soil.

Stabilizer Application. The distribution of lime and cement can be performed dry by either spotting bags on the roadway (Figure 28) or by applying bulk stabilizer from suitably-equipped self-unloading transport trucks (Figure 29) or from other bulk haul units through mechanical spreaders (Figure 30). The use of bagged lime is generally the simplest but also the most costly methods. The disadvantages of the

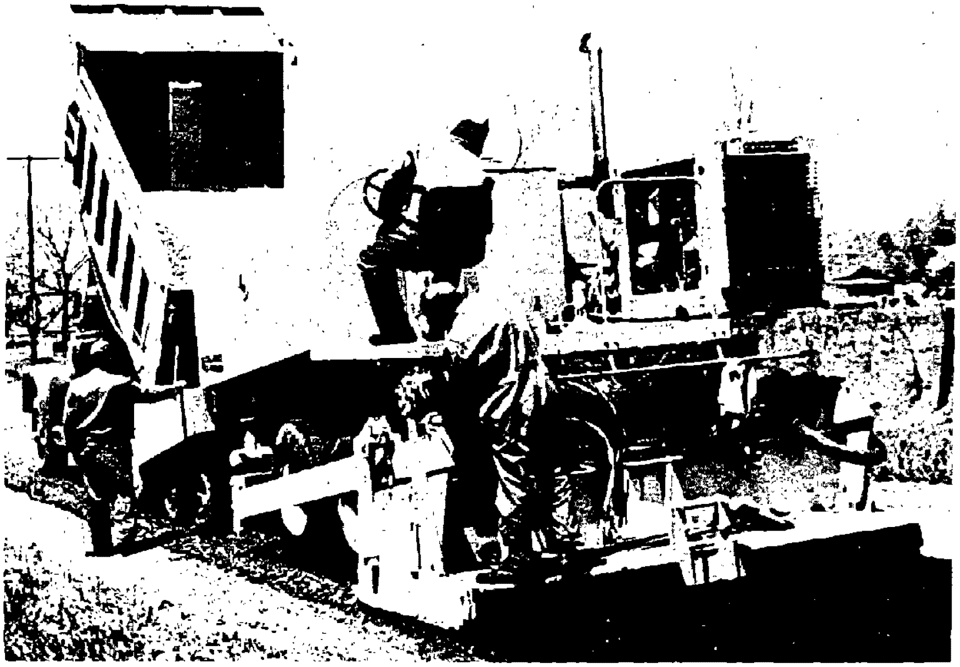


Figure 20. Hopper-type pugmill travel plant (52).

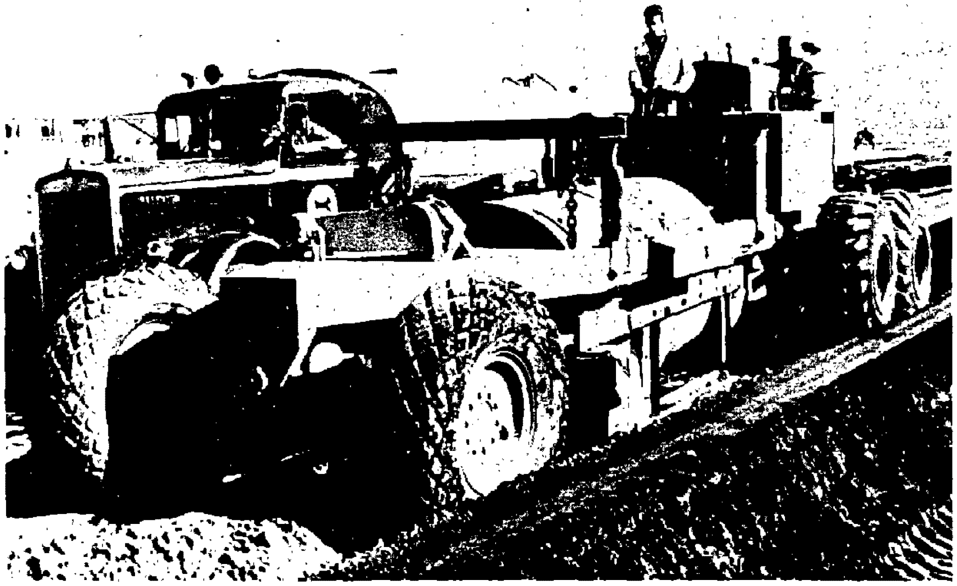


Figure 21, Windrow-type pugmill travel plant (52).

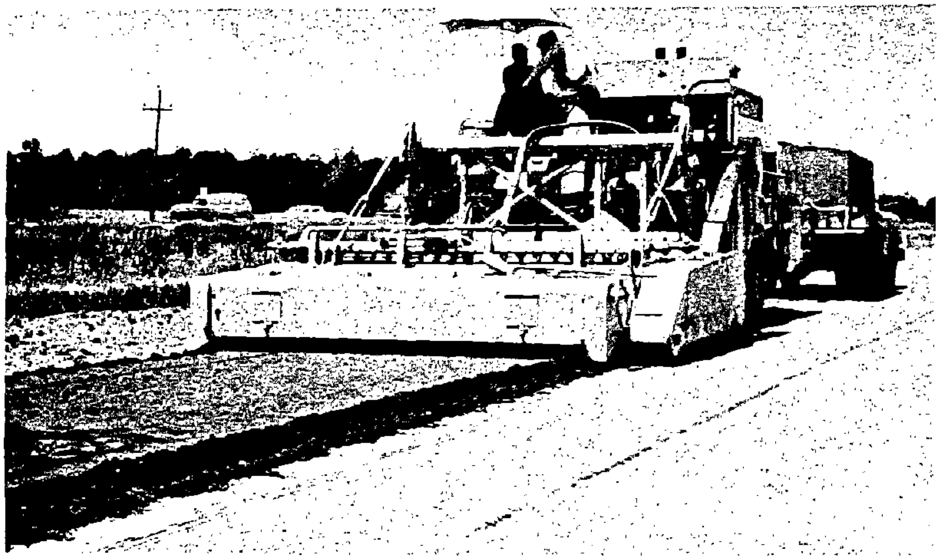


Figure 22. Single transverse shaft rotary mixer (flat type) (51).

Figure 23. Multiple transverse shaft rotary mixer (flat type) (51).

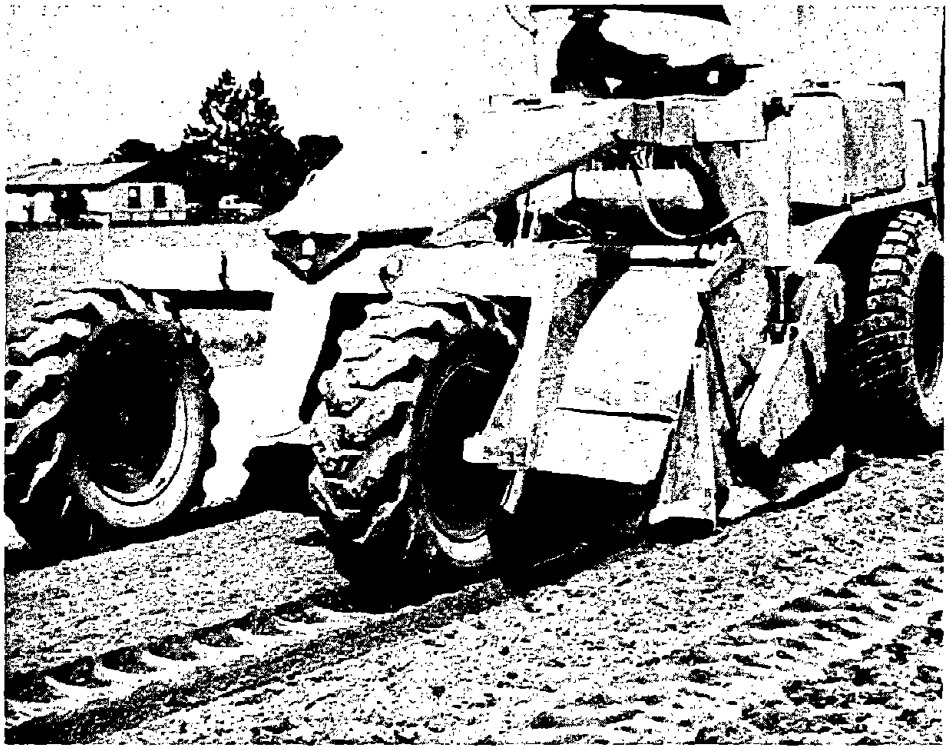


Figure 24. Single transverse shaft rotary mixer (51).

Figure 25. Mixing with motor grader (52).

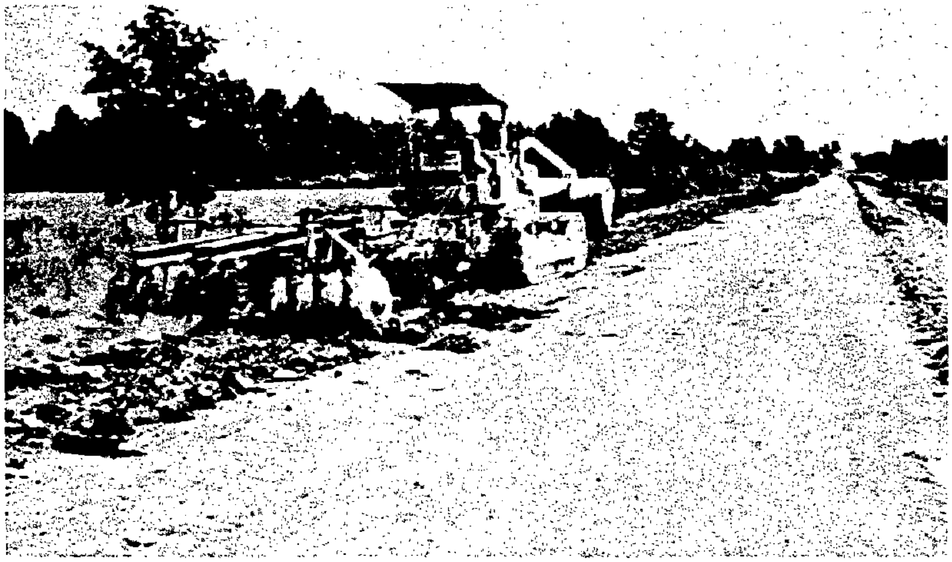


Figure 26. Scarification of clay subgrade with disc harrow (47).

Figure 27. Scarification with motor grader (47).

Figure 28. Bagged lime application showing bag spacing for 4% distribution on worn-out city street (47).

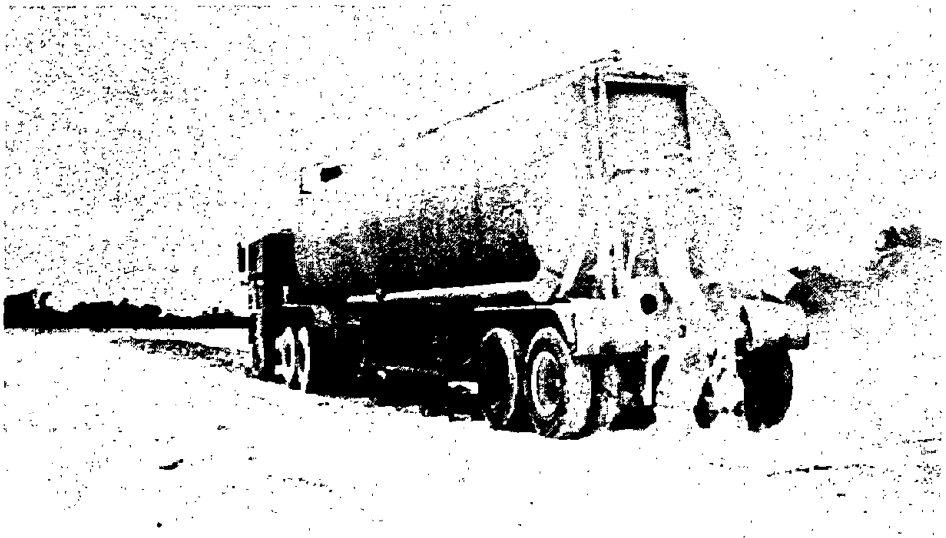


Figure 29. Spreading bulk lime from pneumatic tanker truck through cyclone spreader (47).

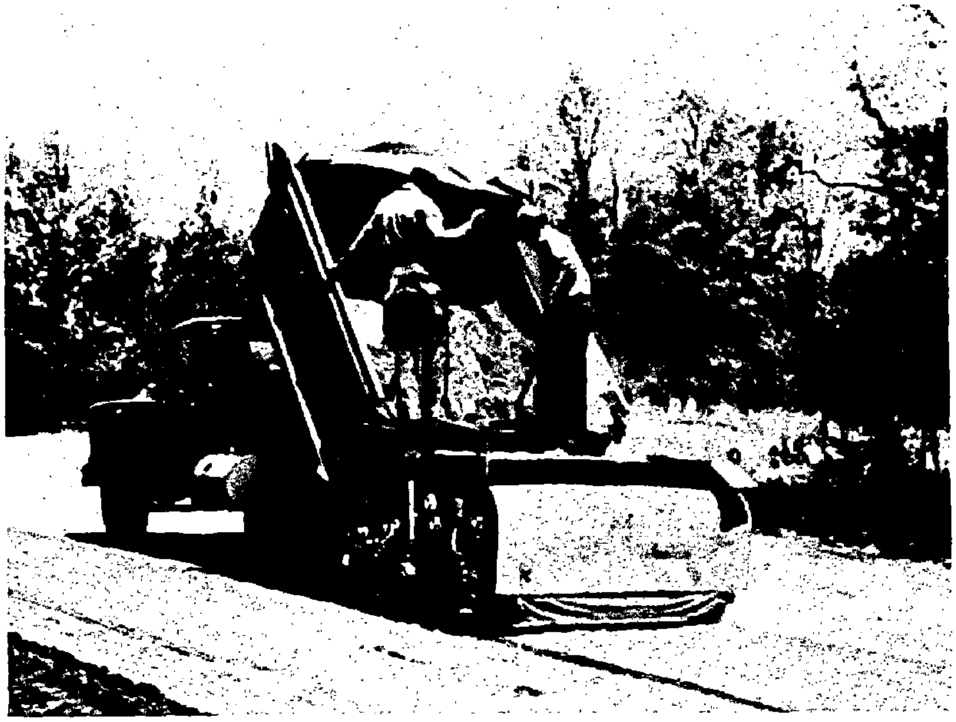


Figure 30. Mechanical cement spreaders should be operated at a constant, slow speed and a uniform amount of cement should be maintained in the hopper (47).

bag method over the dry bulk method are greater labor costs and a slower production. In spite of these disadvantages, bagged lime appears to be most practical for small projects, such as streets (providing dust is controlled), secondary roads, and maintenance patching.

For large stabilization projects, particularly where dusting is not a problem, the use of bulk lime distribution is a common practice. In most cases lime can be distributed from the transport truck.

In most lime-fly ash stabilization projects, lime and fly ash are spread separately. However, it is possible to preblend these two components before spreading. When the lime and fly ash are preblended, it is necessary that they be stored in a dry state. The preblend is normally spread in the dry condition. If lime and fly ash are spread separately, normal lime spreading techniques are utilized. Nearly all fly ash is spread in the conditioned state (i.e., residual moisture content of 15 to 25 percent). It is possible to spread dry fly ash from pneumatic trucks, but dusting is often severe. Conditioned fly ash is normally delivered in open dump trucks, dumped, and spread with a motor patrol, spreader box, or other types of spreaders.

Slurry distribution methods can be used for lime distribution. Hydrated lime and water is mixed in a central mixing tank, jet mixer, or in a tank truck. After mixing in proportions of about 1 ton of lime to 500 gallons of water (500 kg of lime to 1 m^3 of water), the slurry is spread over the scarified roadbed through tank truck spray bars either by gravity or pressure (Figure 31) or the slurry can be added to the soil during the mixing operation (Figure 32). The major advantage of the slurry method is the prevention of the dusting problem. In addition, this method combines lime spreading and watering operations into one, thereby cutting construction costs. Furthermore, this method generally promotes uniform lime distribution. Disadvantages of the slurry method include purchase or rental of the slurry mixing equipment, low production, and unsatisfactory use with wet soils.

Asphalt is spread or distributed from an asphalt distributor Figure 33) or during the mixing process through the mixing machine (Figure 34). The preferred method of asphalt application is through the mixing equipment with built-in spraying systems. The asphalt application rate is matched to the thickness and width of the mixer, forward speed of the mixer, and the density of the in-place soil. When rotary type mixers are utilized which are not equipped with spray bars, an asphalt distributor, operating ahead of the mixer, applies asphalt to the aggregate. Incremental application of asphalt and passes of the mixer are usually required to achieve the specified mixture. It is important for the soil to be at the proper moisture content prior to application of the asphalt, if uniform mixing is to be achieved.

Double Application. Double application of lime is often required when extremely plastic clays are encountered (P.I. of 50 or greater). Lime is added in two increments to facilitate adequate pulverization and obtain uniform mixing. Typically 2 to 3 percent lime is added, partially mixed, and the layer is lightly rolled to seal the surface. After a 24- to 48-hour period pulverization is attempted, the final lime application made, and the mixing of the lime and soil completed.

It is important to remember that the primary objective of the stabilizer spreading operation is to achieve uniform distribution of the stabilizer in the proper proportions. Field experience has indicated that mixing by itself will not greatly improve uniformity of distribution. Hence, an important part of quality control is stabilizer spreading.

Pulverization and Mixing. Single- and multiple-shaft rotary (flat type) mixers are typically utilized to pulverize and mix lime, lime-fly ash, cement, and asphalt with subgrade soils. Motor graders and agricultural type equipment can be utilized; however, the desired uniformity of mixing is not always obtained. Mixing difficulty increases with increasing fineness and plasticity of the soils being treated. In-place mixing efficiency, as measured by the strength of the treated soil, may be only 60 percent to 80 percent of that obtained in the laboratory. This reduced efficiency is sometimes accounted for by

Figure 31. Transit mixing of lime slurry on city street project, using recirculating pump at rear. Pressure and gravity spray bars distribute lime evenly (47).

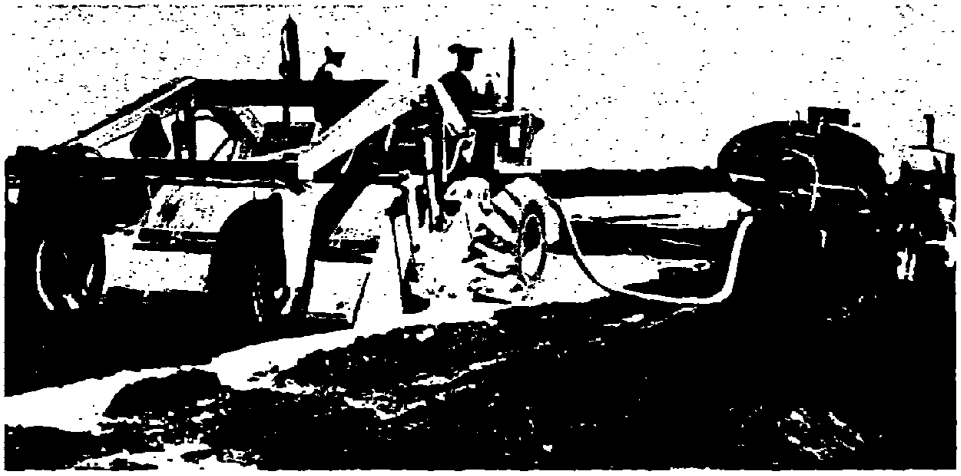


Figure 32. Rotary mixer used for simultaneous mixing of lime and water in clay subgrade soil on Interstate project in California (47).

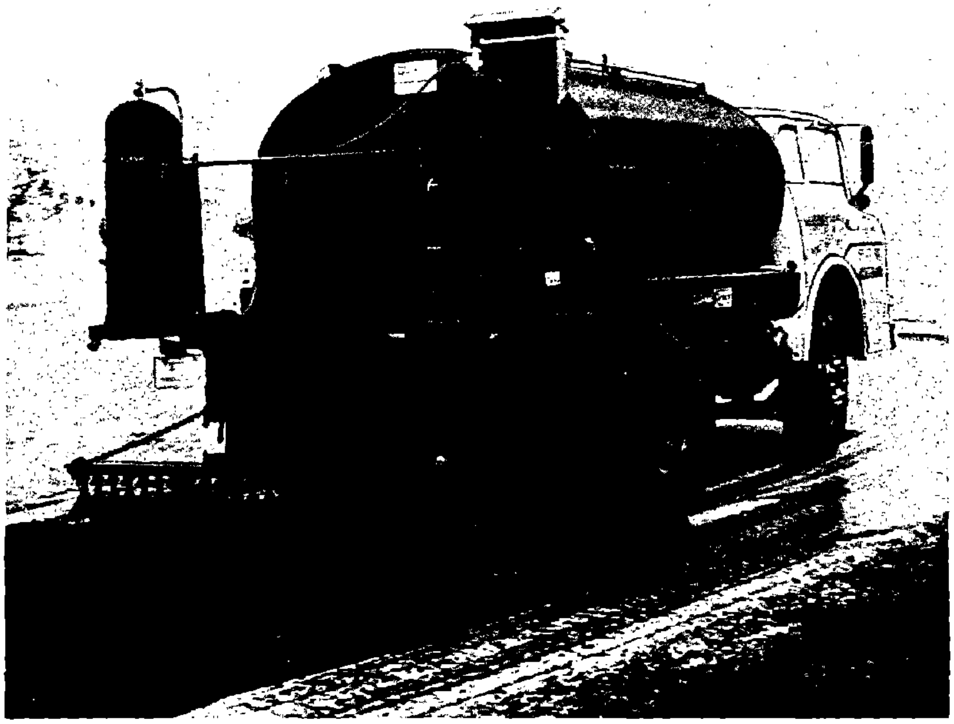


Figure 33. Distributor applying asphalt (52).

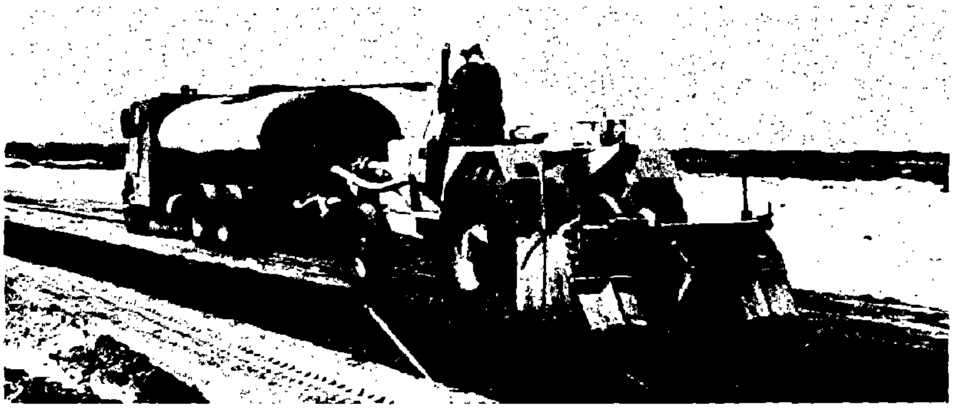


Figure 34. Single-shaft rotary mixer with asphalt supply tank (52).

increasing the stabilizer content from that determined in the laboratory testing program by one or two percent. Windrow and hopper type mixers are not typically used in subgrade stabilization operation.

For lime stabilization, pulverization and mixing should continue until 100 percent of the soil binder passes a 1-inch screen and at least 60 percent passes the No. 4 sieve. Water contents consistent with good compaction should be obtained during the pulverization and mixing operation. For soil cement mixtures, most specifications require that fine grained soils be pulverized such that at the time of compaction 100 percent of the soil-cement mixture will pass a 1-inch sieve and that a minimum of 80 percent will pass a No. 4 sieve, exclusive of any gravel or stone.

Mixing and pulverization requirements for lime-fly ash and cement-fly ash mixtures are typically those for lime and cement stabilization. It is important that uniform mixing be achieved because two stabilizers are being utilized and both must be mixed uniformly to achieve the desired result.

In-place mixing of cement or cement-fly ash and dry uniform, fine sand is impractical for trafficability reasons.

Mixing of asphalt with soil and water should continue until a uniform mixture is obtained. When flat-type rotary mixers and motor graders are utilized, the asphalt spreading and mixing operation requires several repetitions of asphalt distribution and mixing.

Compaction. Compaction should commence as soon as possible after uniform mixing of water and the stabilizer when lime-fly ash, cement-fly ash, and cement are used as stabilizers. Most specifications require that materials be compacted within four hours of mixing and always be complete on the same day the soil is mixed with the stabilizers.

For maximum strength, lime-stabilized soils should be compated soon after mixing, provided uniform mixing is achieved. Since the reactions associated with lime stabilization are longer term as compared to cement stabilization, additional time is available for mixing and pulverizing lime stabilized soils. This additional time is particularly useful when highly plastic soils are being treated and pulverization is difficult.

Experience has shown that breakdown rolling of emulsified asphalt mixes should begin immediately before, or at the same time as, the emulsion starts to break. At about this time, the moisture content of the mixture is sufficient to act as a lubricant between the aggregate particles, but is reduced to the point where it does not fill the void spaces, thus allowing air void reduction under compactive forces. Also, by this time, the mixture should be able to support the roller without undue displacement.

When using cutback asphalt, correct aeration will be achieved when volatile content is reduced to about 50 percent of that contained in the original asphaltic material, and the moisture content does not exceed 2 percent by weight of the total mixture (refer to ASTM D 1461 or AASHTO T 110).

Various types of rollers and layer thicknesses have been used in stabilization operations. For example, in lime stabilization the most common practice is to compact in one lift using the sheepsfoot roller (for fine-grained soils) until it "walks out". The sheepsfoot is often followed by a multiple-wheel pneumatic roller; the flat wheel roller is used for finishing. Single lift compaction can also be accomplished on some of the more granular soils with vibrating impact rollers or heavy pneumatic rollers, with pneumatic or steel rollers used for finishing. When light pneumatic rollers (less than 8 tons) are used alone, compaction is generally done in thin lifts, usually 1 1/2 to 2 inches (40 to 50 mm). Slush rolling of lime-stabilized materials with steel wheel rollers is not recommended. During compaction, light sprinkling may be required, particularly during hot, dry weather, to compensate for evaporative losses.

Since lime-fly ash and cement-fly ash materials often behave as if they are basically granular in nature, with little or no cohesion at the time of compaction, pneumatic-tired rollers steel and vibratory rollers, are usually most effective in providing initial densification of the mixes. Lift thicknesses of 6 inches (150 mm) are common.

Cement stabilization of fine-grained soils sometimes makes use of sheepsfoot rollers. Typically, pneumatic and steel wheel rollers and vibratory rollers are adequate for the granular cement stabilized materials.

Asphalt stabilized materials are granular. Thus, pneumatic, steel wheel, and vibratory rollers can be utilized. Typical types of compaction equipment are shown on Figures 35 to 38.

Placement of multiple lifts of stabilized materials create certain problems that must be recognized by the engineer. Consecutive lifts of lime stabilized materials can be placed successively provided the top approximately 1/4 inch (6 mm) is removed prior to placing the next layer. Carbonation of the top of lime stabilized layers often results when sprinkling is used for curing. The carbonation creates a weak interlayer.

When liquid asphalts are utilized it is important that the lifts have sufficient time to cure prior to placement of the next layer. One week delays in hot, dry weather normally result in the desired curing.

Curing. Proper curing of lime, lime-fly ash, cement-fly ash, and cement stabilization is important because the strength gain is dependent upon time, temperature, and the presence of water. Generally a 3- to

Figure 35. Initial compaction of lime-soil mixture with sheepsfoot roller (47).

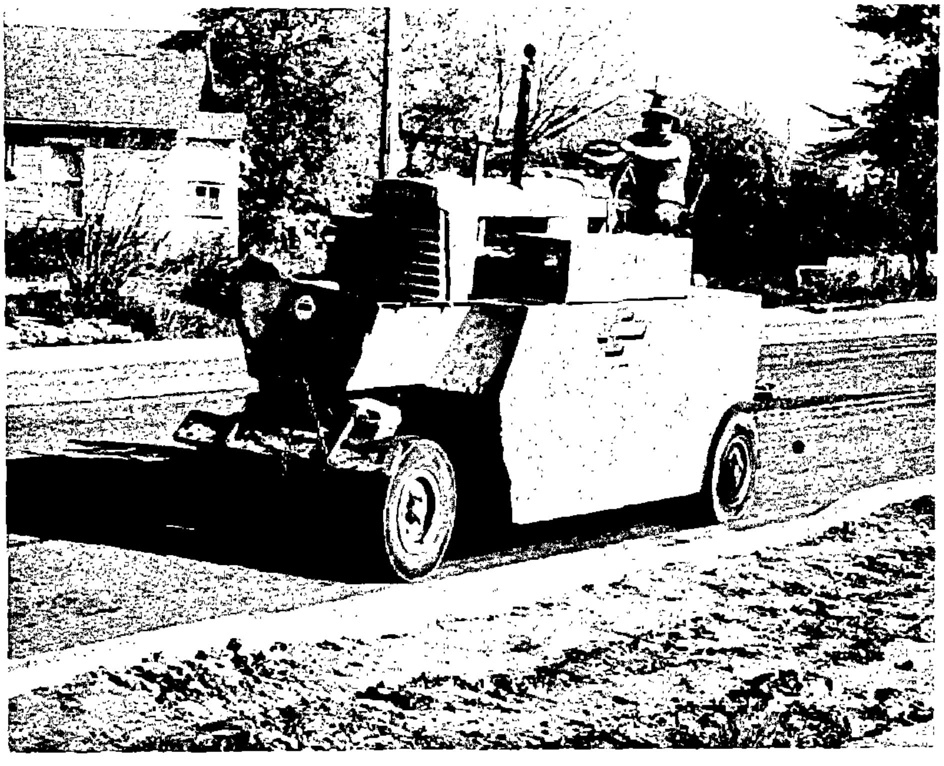


Figure 36. Pneumatic tired roller (47).

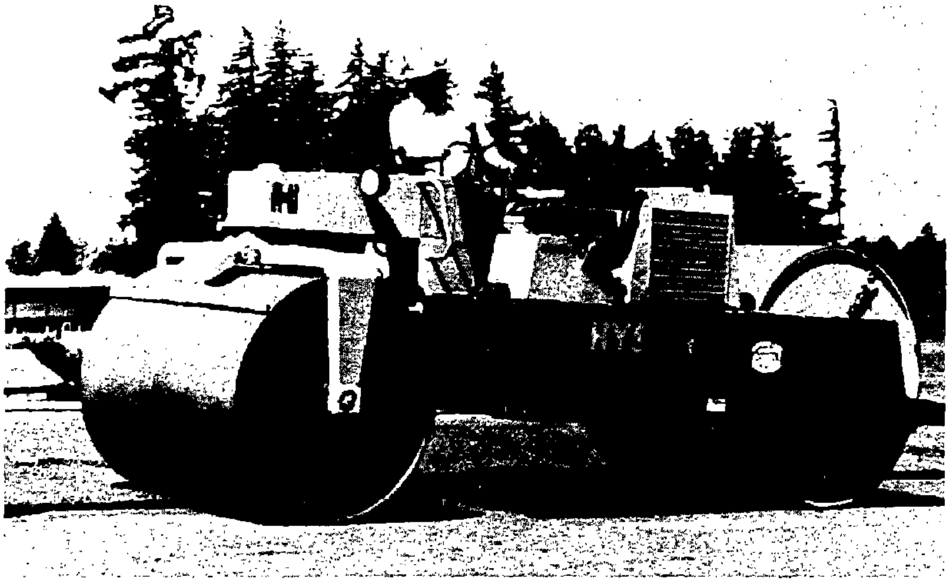


Figure 37. Steel-wheel tandem roller (52).

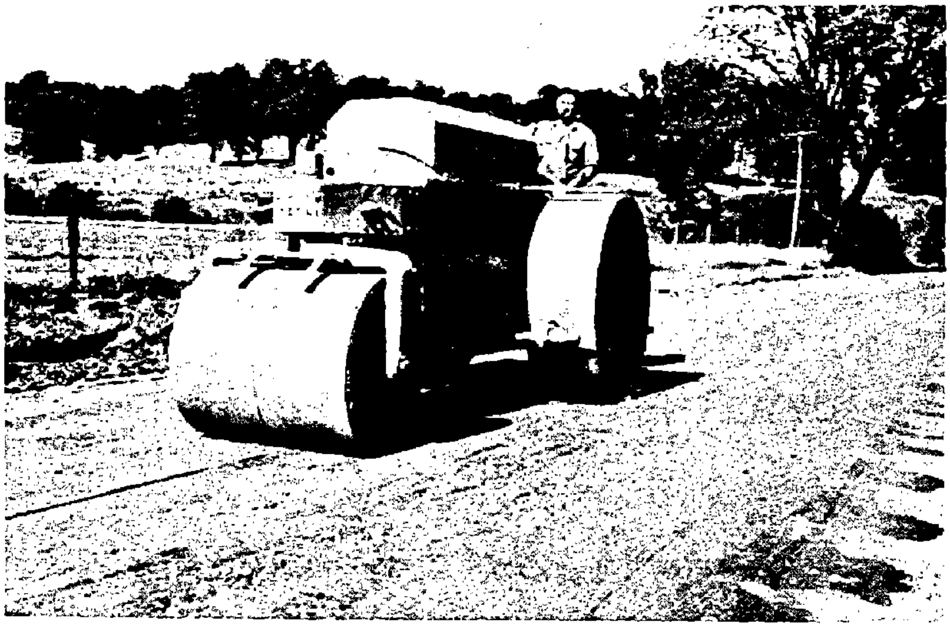


Figure 38. Flat three wheel roller used for final compaction of lime-treated base on farm-to-market road (47).

7-day curing period is required, during which time equipment heavier than pneumatic rollers is kept off. Two types of curing are employed to ensure that the moisture is retained in the stabilized layer--sprinkling (Figure 39), and membrane (Figure 40). Sprinkling with water to keep the surface damp, together with light rolling to keep the surface knitted together, has proven successful. However, the preferred method is membrane curing. In membrane curing, the stabilized soil is either sealed with one shot of cutback asphalt (0.10 to 0.25 gal/sq.yd. (0.5 to 1.2 litres/m^2)) within one day after final rolling or primed with increments of asphalt emulsion applied several times during the curing period. In some cases curing may not be extensive or not needed if the overlying pavement layer is placed shortly after construction of the stabilized layer.

If traffic is to use emulsion or wetback stabilized materials, it is desirable to place a sand or aggregate seal. A protective layer should not be used soon after construction, if traffic will not immediately use the facility as strength gain of cutback and emulsion stabilized materials is based on loss of volatiles. A protective seal will reduce the rate of loss of volatiles.

Subbase and Base Course Stabilization

Stabilization of subbase and base course materials in-place is very similar to subgrade stabilization discussed previously. The major difference in the two operations is the usual use of borrow material and thus the opportunity to distribute the stabilizer and perform mixing with the aid of a windrow. The following construction steps are typically employed for subbase and base stabilization where windrows are employed:

1. Soil preparation,

2. Stabilzier application,

3. Pulverization and mixing,

4. Compaction, and

5. Curing.

As may be noted, most of the construction operations are identical to those for subgrade stabilization. Thus, details will not be restated.

Soil Preparation. The most important element of this operation is to ensure that the underlying course is compacted and to the proper grade and cross slope. The desired density of stabilized subbase cannot be obtained if a soft or undercompacted subgrade is present. A compaction platform therefore must be created and soft spots removed and reworked.

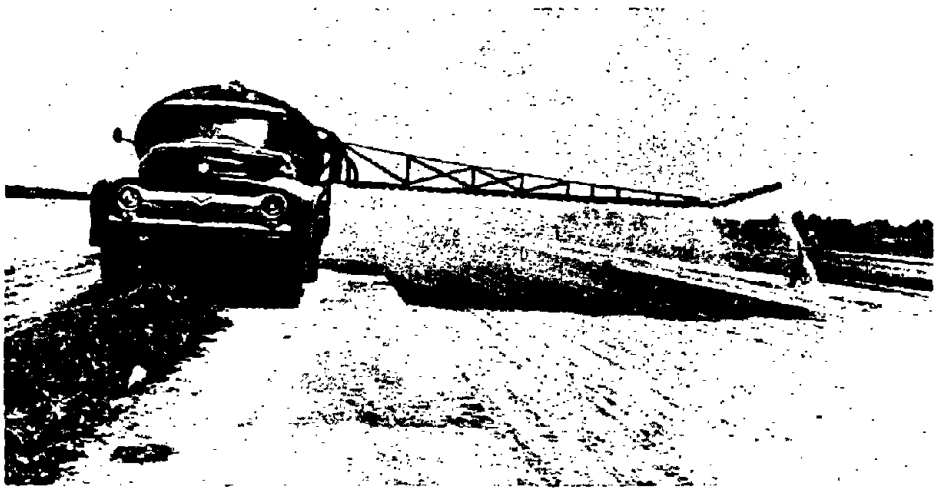


Figure 39. Sprinkling lime-treated subgrade on military jet runway (47).

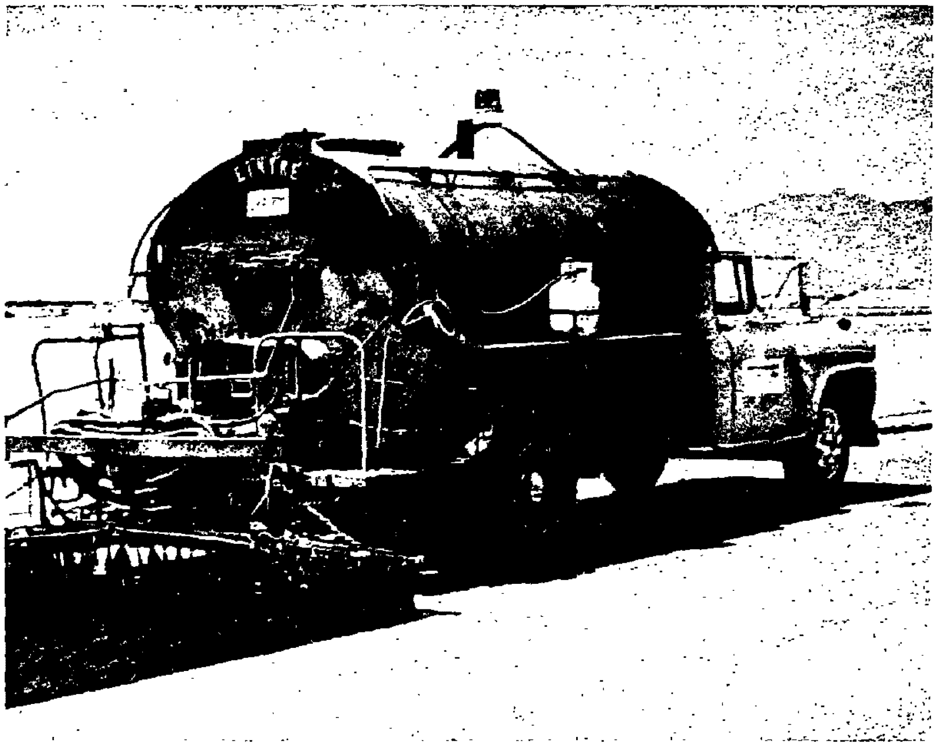


Figure 40. Membrane curing with asphalt (51).

reworked.

Another important element of the soil preparation operation is the formation of a uniform windrow. A windrow sizer may have to be utilized to achieve the desired uniformity (Figure 41).

If the stabilized layer is of sufficient thickness to require multiple lifts, partial surface scrificiation of the bottom lift is often required for lime, lime-fly ash, cement-fly ash, and cement stabilization. For some lime stabilization jobs, it may be necessary to remove the top 1/2 to 1 inch (12 to 25 mm) of material, as this area may be weakly cemented with calcium carbonate rather than the desired pozzolanic action.

Since most borrow materials are granular, pulverization prior to the addition of the stabilizer is not required. If clay soils are encountered or if the stabilized borrow contains clay, partial pulverization may be required prior to the addition of the stabilizer.

Stabilizer Application. The most common form of stabilizers for use in windrows is bulk. Lime and cement can be distributed conveniently with bulk trucks or with specially designed trucks as shown on Figure 42. Fly ash is normally conditioned with moisture prior to spreading; however, dry distribution is possible if windrows are utilized.

Asphalt can be distributed through the mixer (Figure 34) or by distributors as shown on Figure 33. Lime slurries can be used to distribute the lime in mixers (Figure 32).

The addition of water prior to the introduction of asphalt into the windrow is often necessary in asphalt stabilization operations. This water (usually 3 to 5 percent) will aid mixing. Dry soil and cement or lime should be premixed prior to the addition of water for best uniformity. The higher plasticity index soils will require an increase in water.

Pulverization and Mixing. Mixing of materials in windrows can best be performed by parallel-shaft travelling pugmill mixers. The machine moved along the windrow, picking up the material, mixing it with stabilizer (and water as needed) in the pugmill, and depositing the mixture in a windrow ready for spreading and compaction. It is not unusual to require more than single-pass mixing. Additional mixing can often be performed with the motor grader prior to spreading and compaction.

The hopper-type travel plants are sometimes used for subbase and base course stabilization. Aggregate is deposited in the hopper and mixed with the proper amount of stabilizer in the mixing chamber. Good stabilizer distribution is normally obtained if the operation is carefully controlled.

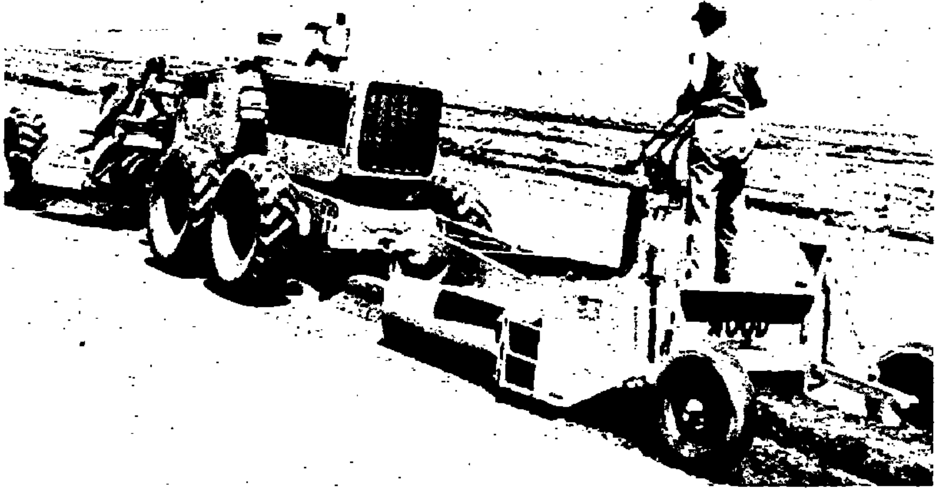


Figure 41. Windrow sizer (52).

Figure 42. Windrow-type mechanical spreader is used to place cement on top of windrow of soil (51).

When asphalt is used in combination with lime, cement or fly ash water should be added and mixed before the asphalt is entered into the system.

Compaction and Curing. These operations are identical to those utilized in subgrade stabilization. It is important, however, to recognize that additional aeration of emulsion, and cutback stabilized materials may be required if windrow or hopper-type mixers are utilized because the mixing operation affords only limited opportunities for the volatiles to escape.

CENTRAL PLANT

Central plant mixing operations afford the best opportunity to produce uniform stabilized materials and can achieve close to 100 percent mixing efficiency as measured by the strength of the treated soil measured after field versus after laboratory mixing. Of the two major types of central plants, the batch plant will normally have better uniformity and control than the continuous plant.

Both hot and cold mixing operations can be performed with central plants. Asphalt cements normally require hot central plants for mixing, although soft asphalt cements and foamed asphalt cements have been utilized on mixed-in-place operations. Emulsified asphalts and cutback asphalts have been used in hot processes where temperatures are typically in the range of 150 to 220°F (65.6 to 104.4°C). Emulsion and cutbacks, however, can be used in central plants without the use of heated aggregates. Both continuous (Figure 43) and batch type (Figure 44) hot plants are available and are used extensively.

Cold central plant mixing operations have been used for lime, lime-fly ash, cement-fly ash, and cement stabilizations (Figure 45). Continuous plants are used more often than batch type plants due to their high production capabilities. Pugmill type mixing chambers on the continuous and batch plants are most popular, although central mix portland cement concrete plants have been used for cement and lime-fly ash stabilization projects.

Typical central plant mixing construction operations consist of the following:

1. Receiving and storage of materials,
2. Mixing,
3. Hauling,
4. Spreading and
5. Compaction.

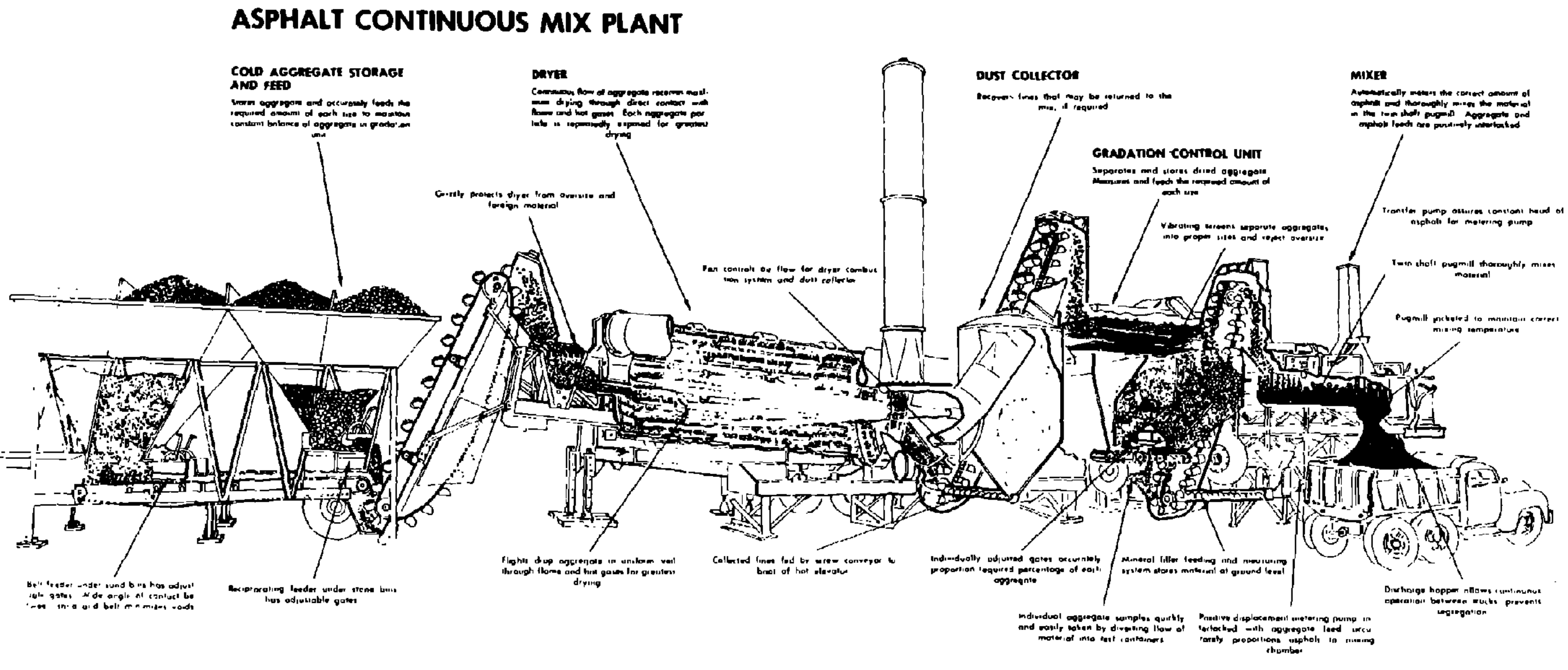


Figure 43. Asphalt continuous mix plant (52).

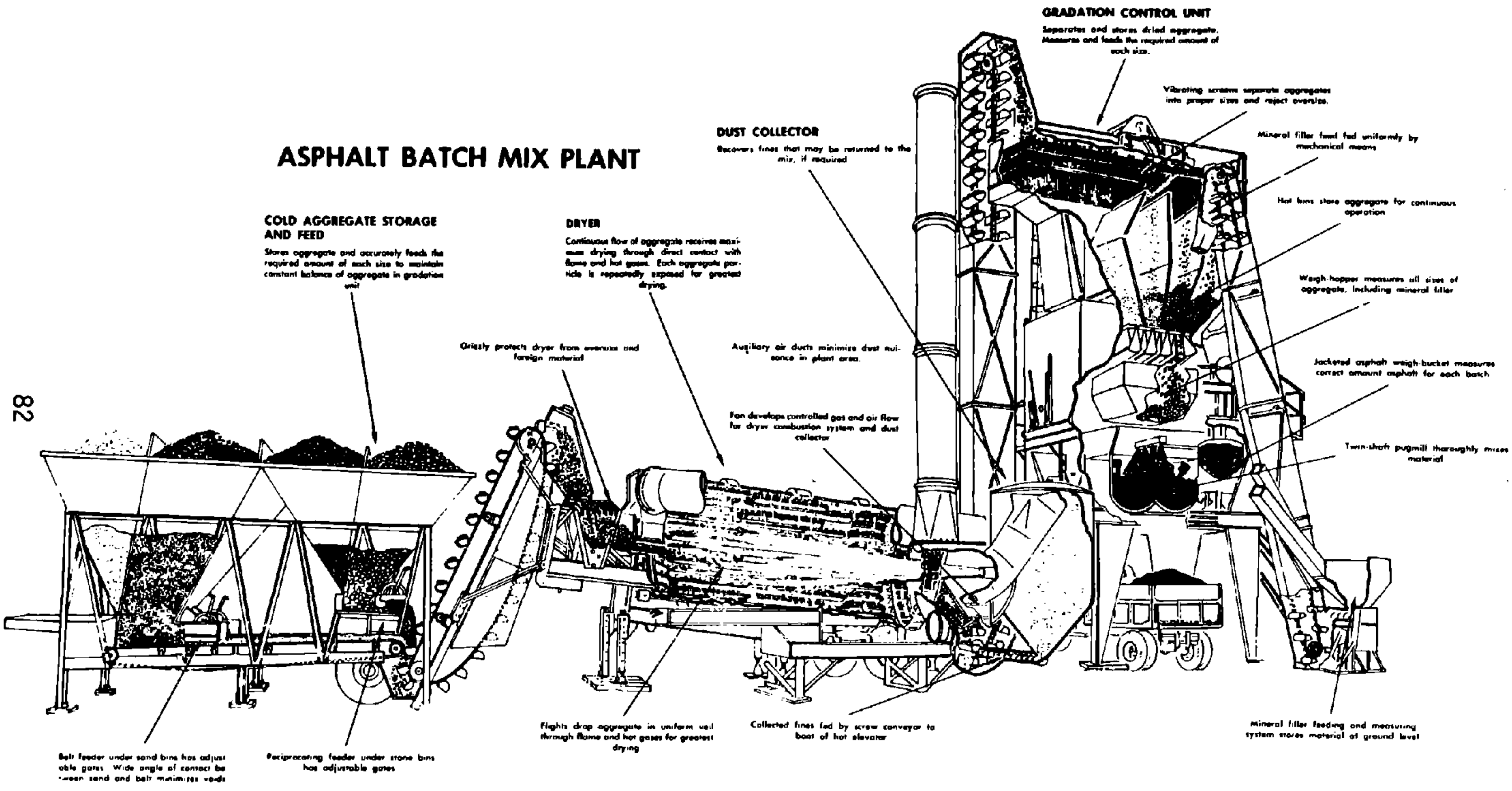


Figure 44. Asphalt batch mix plant (52).

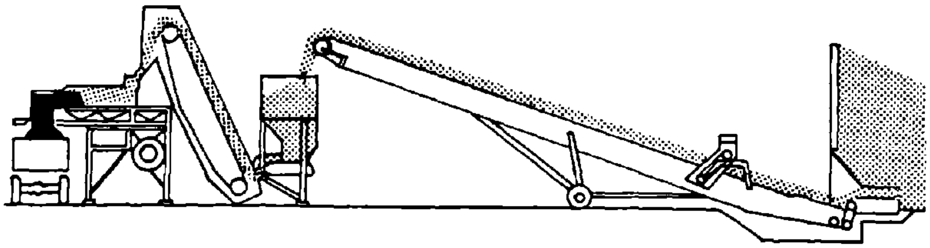


Figure 45. Flow diagram of a typical cold mix continuous plant (52).

The primary difference between hot and cold central plant mixing operation is the heating of the aggregates and stabilizers prior to mixing. Typical central plant operations are summarized below.

Receiving and Storage of Materials

Stabilizers and borrow material (aggregates) must be stored at the plant site. Typically lime and cement are stored in vertical silos and delivered to the plant by gravity and compressed air. For continuous plants where lime and cement are metered volumetrically, the stabilizer is usually transferred from the large storage silos to small feed trucks capable of supplying a continuous, calibrated feed.

Asphalt materials are normally stored in heated storage tanks. The temperatures of these tanks are adjusted to provide the correct asphalt viscosity for mixing.

Fly ash is normally stored in open stockpiles which have been conditioned with sufficient water to prevent dusting (usually 15 to 25 percent moisture). During dry weather, the stockpile surfaces must be kept moist or the stockpile covered to prevent dusting. Conditioned fly ash is normally charged into a feed hopper prior to mixing.

Aggregate materials are normally stored in stockpiles and fed through a belt, cold feed system. Sufficient stockpiles to provide the desired gradations should be utilized. They may vary from one to four in number. Variable speed feeder belts are desirable at the cold feed.

A water storage tank or a well with pressure system can be utilized to handle the water required for mixing and compaction.

Mixing

Mixing must be accomplished in such a way that the proper amount of stabilizer is uniformly distributed. Plants suitable for this purpose have been discussed previously.

Hauling

Lime, lime-fly ash, cement-fly ash, and cement stabilized mixtures which are blended in a central plant location can be hauled to the road site in conventional, open-bed dump and bottom dump trucks. If haul distances are long or drying of the material enroute poses a problem, then provisions should be made to cover the trucks with tarpaulins or other suitable covers to prevent loss of moisture or scattering of environmentally objectionable dust along the haul routes.

Dusting is rarely a problem with asphalt stabilization operations. However, tarpaulins or other suitable covers are used to prevent heat loss when long hauls are required on cold days.

Sufficient trucks should be made available so that all equipment such as the mixing plant, spreaders, rollers, etc., can operate at a steady, continuous pace rather than on a stop-and-go basis.

Spreading

Spreading should be accomplished as uniformly as possible and with a minimum of segregation. Spreader boxes (Figures 46 and 47), laydown machines (Figure 48), and other equipment with automated grade control are recommended. An alternate method of spreading (sometimes used but not recommended) is to place the stabilized material in windrows from trucks and spread with road graders. With the windrow operation, care must be taken not to overmanipulate the stabilized material, which may cause segregation and drying.

Layers of stabilized mixtures are normally spread to a thickness of between 15 and 30 percent greater than the desired final thickness to attain the required compacted thickness. The amount of excess thickness is a function of the aggregate type and source, as well as the method of spreading. Some experimentation may be necessary to determine the proper spread thickness for each operation, because some types of spreading operations provide a degree of initial consolidation. The maximum recommended thickness for a single stabilized layer after compaction is 8 to 10 inches (200 to 250 mm), with some agencies specifying a 4 inch (100 mm) maximum or less. If thicknesses of lime, lime-fly ash, cement-fly ash, and cement layers greater than the specified maximum are needed to develop an adequate pavement system, the material should be spread and compacted in lifts. If the material is placed in

Figure 46. Towed-type spreader (52).

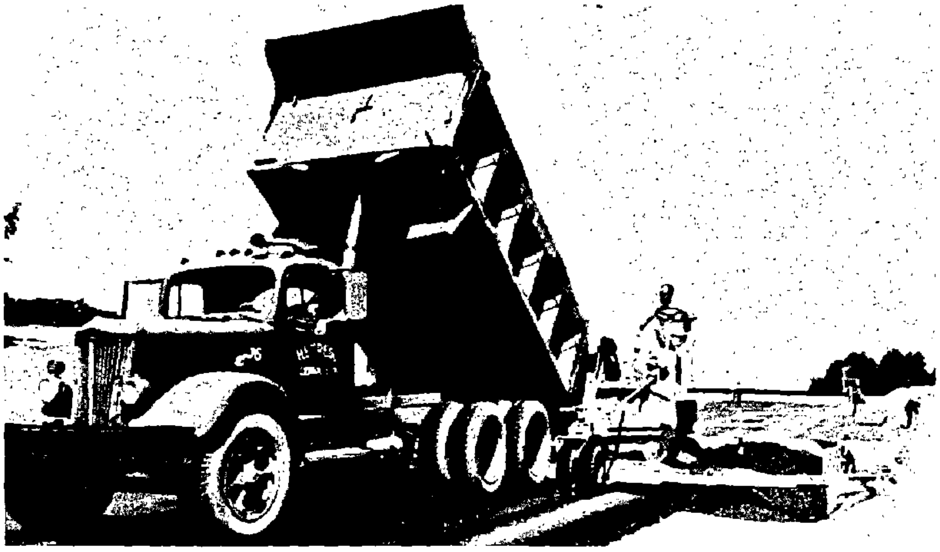


Figure 47. Placing lime-fly ash-gravel mixture with shoulder base spreader (47).

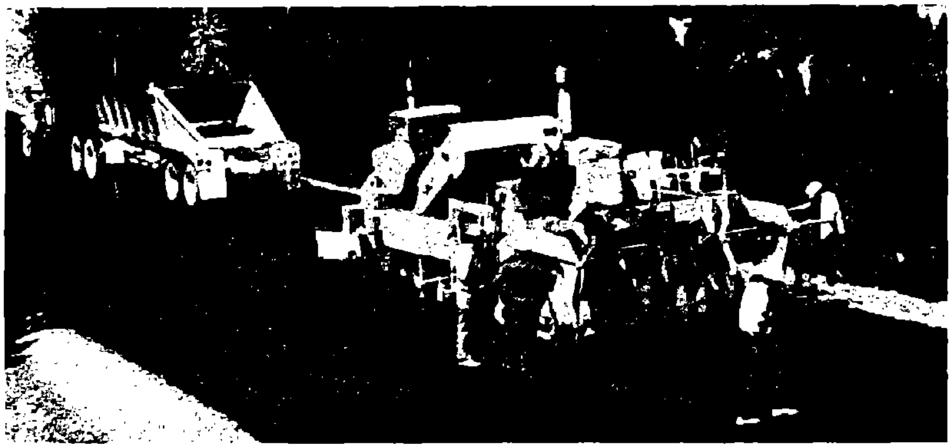


Figure 48. Spreading cold mix with conventional paver (52).

lifts, the time between lifts should be kept as short as possible so that the lower layer has not "set up" before the next layer is placed. If the stabilized material in the lower layer is fresh and the surface free of loose material, the next layer can be spread without scarifying the lower layer. As a general rule, subsequent layers should be placed the same day, but with multiple-layered pavements, such as airport and marine terminal pavements, this is not always possible. If the stabilized mixture in the lower layer has taken on an initial set, steps should be taken to ensure the development of a bond between the two layers. Specifically, steps should be taken to ensure that there is no loose material on the lower layer and that the surface is moist before placing the material for the subsequent layer.

If multiple layers of emulsion or cutback stabilized layers are required to satisfy pavement thickness requirements, a time delay between layers is beneficial to allow for the escape of volatiles and thus for a gain in strength. If multiple layers must be placed with little delay, a longer curing period should be considered for thickness design considerations.

Compaction

This operation is identical to that utilized for mixed-in-place operations with the exception of the urgency of compaction where hot, asphalt stabilization operations are utilized. Break down rolling of asphalt cement stabilized mixtures should be complete before the temperature reaches about 175°F (80°C). However, low internal friction mixtures may require lower temperatures.

SAFETY PRECAUTIONS

Certain safety precautions should be undertaken when stabilizers are utilized. These precautions are listed on Table 14 and are concerned with workman safety as well as the safety of the public in and around the construction site. Dust from the distribution of the stabilizers and the mixing operation are major concerns. In addition, it is sometimes required to work with cutback asphalts above their flash point temperature.

Table 14. Equipment Typically Associated with Mixed-In-Place Subgrade Stabilization Operations.

STABILIZER	CONSTRUCTION OPERATION				
	SOIL PREPARATION	STABILIZER APPLICATION	PULVERIZATION AND MIXING	COMPACTION	CURING
Lime[1]	•Single-shaft rotary mixer (flat type) •Motor grader •Disc Harrow •Other agricultural-type equipment	•Dry-bagged •Dry bulk •Slurry •Slurry thru mixer	•Single- and multi-shaft rotary mixers •Motor graders •Other agricultural-type equipment	•Sheep's foot •Pneumatic •Steel wheel	•Asphalt membrane •Water sprinkling
Lime or cement, Fly ash[2]	•Single-shaft rotary mixer (flat type) •Motor grader •Disc harrow •Other agricultural-type equipment	•<u>Separate application</u> •Lime--dry or slurry •Fly ash--conditioned •<u>Combined application</u> •Dry-bagged •Dry bulk	•Same as lime	•Steel wheel •Pneumatic •Vibratory	•Asphalt membrane •Water sprinkling
Cement[3]	•Single-shaft rotary mixer (flat type) •Motor grader •Disc harrow •Other agricultural-type equipment	•Dry-bagged •Dry bulk	•Same as lime	•Sheep's foot •Pneumatic (clay soils) •Vibratory (granular soils)	•Asphalt membrane •Water sprinkling
Asphalt[4]	•Motor grader •Single-shaft rotary mixer (flat type)	•Asphalt spray distributor •During mixing process	•Single- and multi-shaft rotary mixer (flat type) •Motor grader	•Pneumatic •Steel wheel •Vibratory	•Volatiles should be allowed to escape and/or the pavement to cool

	COMMENTS	SAFETY PROCEDURES
1	Double application of lime may be required to facilitate mixing. The soil and air temperature should be greater than 40°-50°F to insure adequate strength gain. Construction should be completed early enough in summer or fall so that sufficient durability will be gained to resist freeze-thaw action.	Lime spreading should be avoided on windy days. Proper clothing should be worn so that workmen can avoid skin contact with quicklime. Workmen should avoid prolonged contact with lime and breathing lime dust.
2	Fly ash must be conditioned with moisture prior to distribution to prevent dusting. Mixing and compaction should be completed shortly after stabilizer application. The soil and air temperature should be greater than 40°-50°F to insure adequate strength gain. Construction should be completed early enough in summer or fall so that sufficient durability will be gained to resist thaw-freeze action.	Fly ash, lime and cement spreading should be avoided in windy days. Workmen should avoid prolonged contact with the stabilizers and breathing the stabilizers.
3	Mixing and compaction must be completed shortly after stabilizer application. The soil and air temperatures should be greater than 60°F to insure an adequate rate of strength gain. Construction should be completed early enough in summer or fall so that sufficient durability will be gained to resist freeze-thaw action.	Cement spreading should be avoided on windy days. Workmen should avoid prolonged contact with cement and breathing the cement dust.
4	Proper soil moisture content must be achieved to aid distribution and mixing. Stabilized material should be properly aerated prior to compaction. The soil and air temperature should be above 40°F to allow for proper curing and sufficient time for compaction if hot mix processes are utilized. Thick lifts of hot, asphalt cement stabilized materials can be placed below 32°F.	Proper clothing should be worn so that workmen can avoid skin contact with quicklime.

V. EXAMPLE PROBLEMS*

DESIGN EXAMPLE 1

It is desired to construct a secondary road in a rural area of southwest Texas. The soils of the area are primarily sandy. The following data were gathered for planning and design purposes:

a. Soil reconnaissance and boring program results:

% passing No. 4 sieve	90
% passing No. 10 sieve	82
% passing No. 40 sieve	45
% passing No. 60 sieve	40
% passing No. 200 sieve	15
material smaller than 0.05 mm (silt and clay combined)	12
material smaller than 0.001 mm (clay)	9
liquid limit, Wl	20
plasticity index, PI	9
γd_{max} (natural soil), lb/ft^3	130
W_{opt} (natural soil), %	10.0
CBR	10
parent material mostly sandstone and silicious limestone	

b. Traffic data indicates a traffic volume of 500 daily 18-kip equivalent axle loads will use the design lane of the facility over the traffic analysis period.

Step 1

From Figure 7 (Volume 2, Chapter II) the best methods of stabilization of the material soil are: (1) cement stabilization, and (2) bituminous stabilization.

Option 1 - cement stabilization

Step 2

Figure 32 (Volume 2) is used to further evaluate the suitability of this soil for stabilization with cement. The following results are obtained from the analyses outlined in Figure 32 (Volume 2).

pH test for the presence of organic matter .... pH = 12.4 (Volume 2, Appendix B)

---

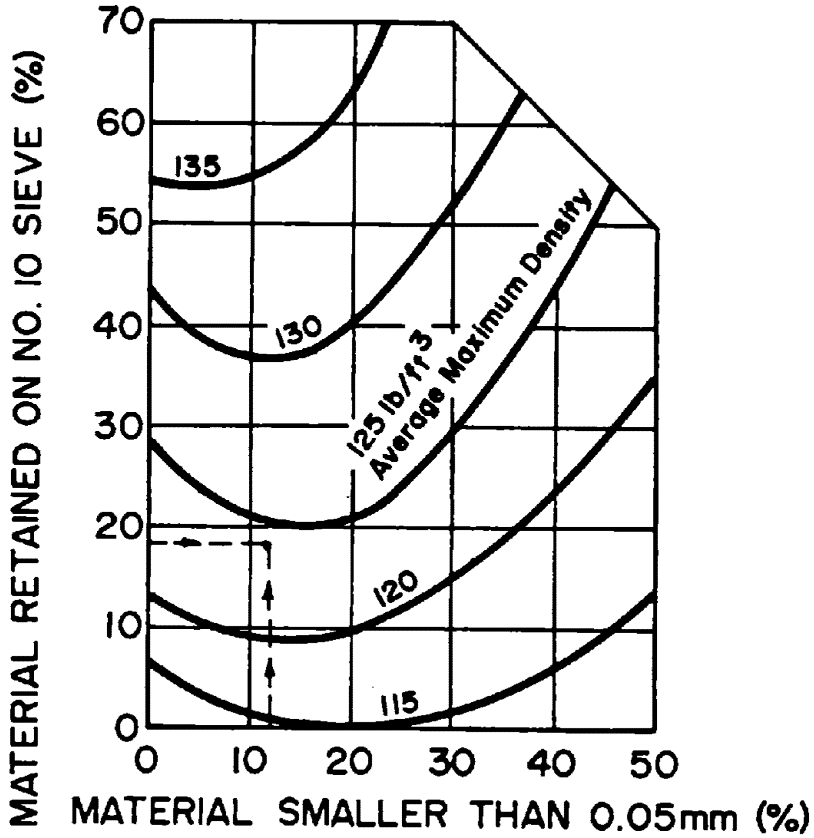
*Only English units will be used in example problems for the sake of clarity.

Sulfate determination ... sulfate content = 0.01%
(Volume 2, Appendix C: Gravimetric Method)

The soil, therefore, does not contain deleterious amounts of organics or sulfate matter.

Step 3

Figure 32 (Volume 2) is again used to design the soil cement mixture. According to this figure, the PCA shortcut test procedure is suitable here to determine the required cement content of the mixture. Below are the results of this analysis.



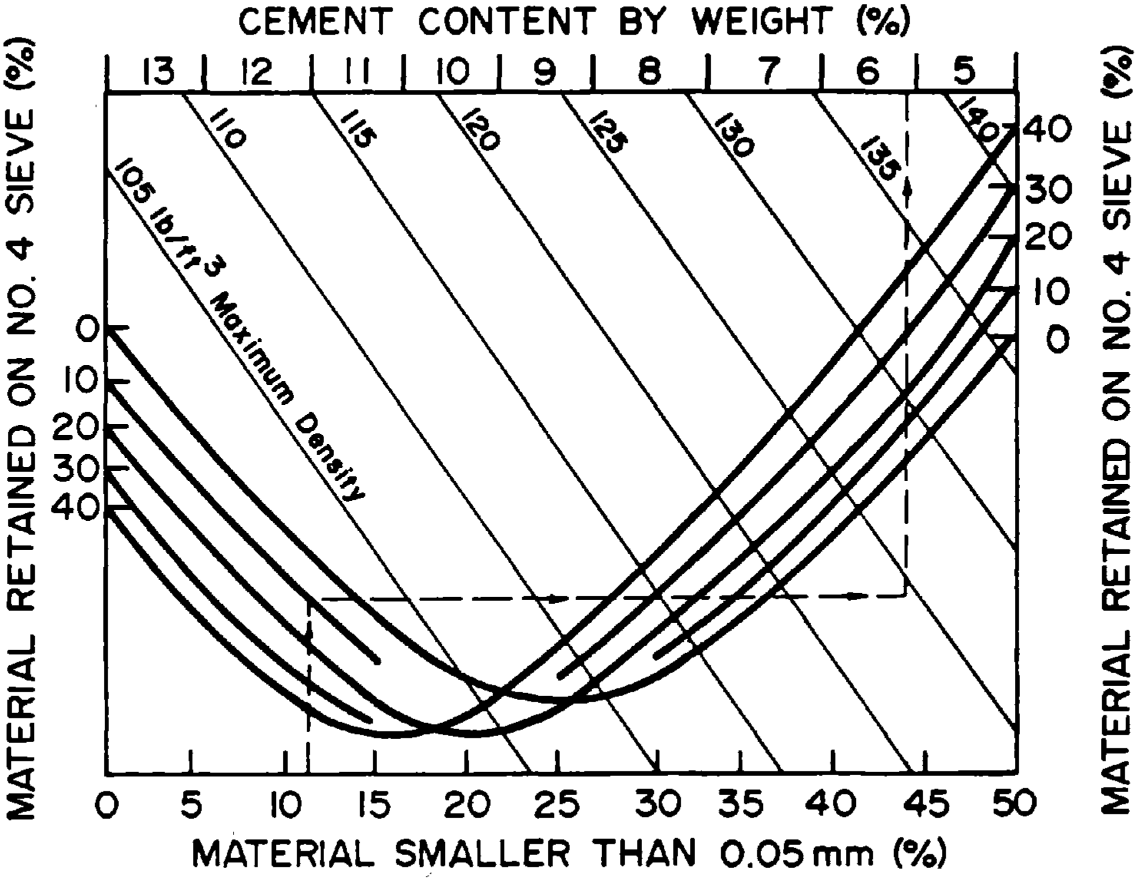
1 lb/ft^3 = 1.602 x 10^1 Kg/m^3

Figure 49. Average maximum densities of soil-cement mixtures containing material retained on the No. 4 sieve (15).

a. Since material is retained on the No. 4 sieve method B of the PCA shortcut procedure is used.

b. Figure 49 indicates that the estimated maximum density of the soil cement mixture is 124 lb/ft^3 since the soil contains 12 percent material smaller than 0.05 mm and 18 percent material retained on the No. 10 sieve.

c. Figure 50 is used to determine the cement content by weight to use in the moisture density test. Since the soil contains 12 percent smaller than 0.05 mm and 10 percent retained on the No. 4 sieve and since the estimated maximum density 124 lb/ft^3, 6 percent cement by weight is required.

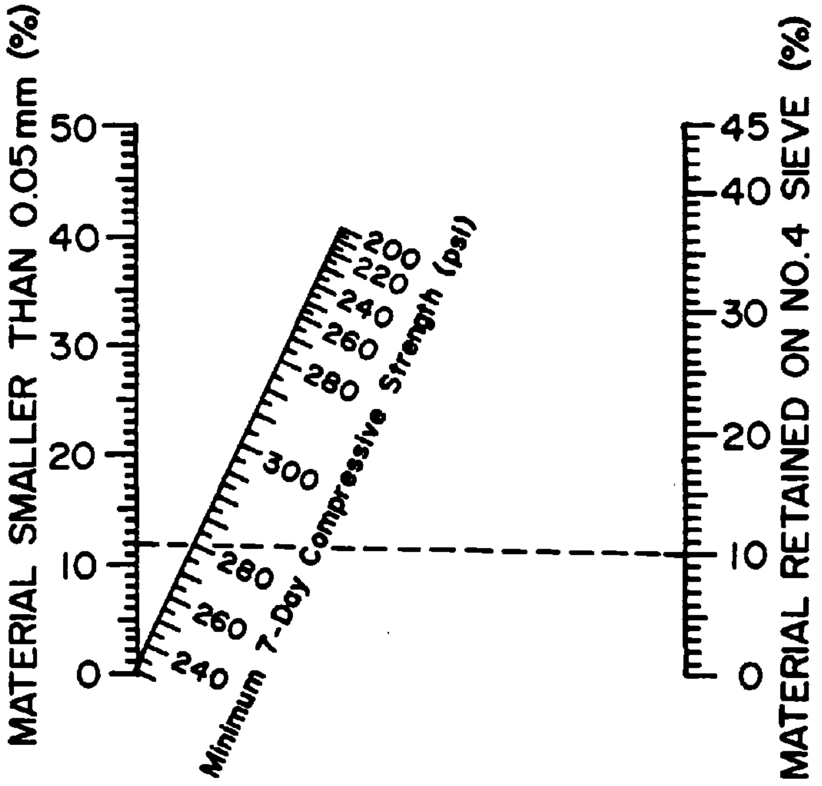


1 lb/ft^3 = 1.602 x 10^1 Kg/m^3

Figure 50. Indicated cement contents of soil-cement mixtures containing material retained on the No. 4 sieve (15.)

d. Using the total material and 6 percent cement by weight, compressive strength test specimens were molded in triplicate at maximum density (124 lb/ft^3) and optimum moisture (11.0 percent). The average 7-day compressive of these specimens were 675 psi.

e. Since the soil contains 12 percent material smaller than 0.05 mm and 10 percent retained on the No. 4 sieve, the minimum allowable compressive strength for this soil mixture is 280 psi, as shown in Figure 51. Since the average mixture compressive strength is 675 psi (see d above), 6 percent cement by weight is adequate.



1 psi = 6.89 x·10^3 Pa

Figure 51. Minimum 7-day compressive strengths required for soil-cement mixtures containing material retained on the No. 4 sieve (15).

If the average compressive strength determined in step d had been lower than the minimum allowable strength as prescribed in Figure 51, 6 percent cement by weight would probably not be adequate. Additional testing would have been required to establish the cement requirement for the soil. These tests involve molding and testing soil-cement specimens in freeze-thaw and wet-dry testing according to ASTM and/or AASHTO procedures.

Step 4

The cement stabilized soil can now be used in the pavement design analysis. The AASHO Interim procedure, found in Volume 2, Chapter III on Thickness Design, will be used for this design analysis.

a. The roadbed soil support value is selected from Figure 3 (Volume 1), as 5.

b. The daily equivalent 18 kip single-axle loads estimated for the design lane for the traffic analysis period is given as 500.

c. The regional factor applicable to the site was selected as 1.25.

d. Figure 2 (Volume 1) is used to compute the weighted structural number, SN. From the data given above, for a terminal serviceability of 2.5, SN = 3.7. Therefore a suitable design is one in which the combination of products of layer thickness and structural layer coefficients equate to 3.7. Table 2 (Volume 1) is now used to help in attaining this SN.

e. Since the structural coefficient of the surface hot mix asphalt at the AASHO Road Test was computed as $a_1 = 0.44$, this value is used for the asphalt concrete surface. An approximate structural coefficient for the soil cement base, a_2, is found from Table 2 as a function of the soil cements unconfined compressive strength. The unconfined compressive strength of 675 psi found in the laboratory is reduced for field design purposes to reflect construction variation and mixing efficiency as follows:

$$\text{Mixing efficiency} = \left(\frac{\text{field mix strength}}{\text{lab mix strength}}\right) = 0.75$$

Field coefficients of variation for mixed-in-place construction = 0.25 (Volume 1, Chapter IV)

$$\text{Design unconfined compressive strength} = 675 \text{ psi } (0.75)(0.75) = 380 \text{ psi}$$

$a_2 = 0.15$ from Table 2 (Volume 1)

f. Obviously, there are many possible layer combinations to achieve a SN of 3.7. Below one alternative is shown.

$D_1 = 6"$ Asphalt concrete, $a_1 = 0.44$

$D_2 = ?$ Cement stabilized
soil used as base, $a_2 = 0.15$

Natural subgrade

$SN = D_1a_1 + D_2a_2 = 6(0.44) + D_2(0.15)$

$3.7 = 6(0.44) + D_2(0.15)$

$\underline{D_2 = 7.0 \text{ in.}}$

Step 5

From Table 20 (Volume 1) the average representative cost of cement stabilized subgrade is \$0.30/yd^2-in. With asphalt concrete at a cost of \$1.00/yd^2-in. an estimated cost for the pavement is \$8.10.

From Table 38 (Volume 1) a total energy consumption for cement treated subgrade in place is 23,700 Btu/yd^2-in. With asphalt concrete utilizing 29,000 Btu/yd^2-in., an estimated energy demand for the pavement section is 339,900 Btu/yd^2.

Option 2 - Bituminous Stabilization

Step 2

Since a mixed-in-place construction method is most suitable for stabilization of the natural soil for this roadway, a liquid asphalt stabilizer was selected. An asphalt emulsion was selected instead of a cutback asphalt because of environmental advantages and energy savings. For these reasons Figure 42 (Volume 2), Emulsified Asphalt Mixture Design Method, is followed here.

a. The type of emulsion was selected from Table 34 (Volume 2). As the aggregate to be stabilized in this in-place mixing operation is dry to damp silty sand, a CSS-1h emulsified asphalt was selected. The selection of a cationic emulsified asphalt was verified by Figures 39 and 40 (Volume 2) for the highly silicious soil.

b. The amount of emulsified asphalt was selected from Table 38 (Volume 2) on a weight basis. With 15 percent passing the No. 200 sieve and 82 percent passing the No. 10 sieve an emulsified asphalt content of 7.9 lbs per lb of dry aggregate is selected. This was verified by CKE testing.

c. Mixing and coating tests were performed in accordance with reference 149. These tests indicated a moisture content of 5.0% should be maintained during field mixing and compaction.

d. Laboratory specimens were mixed, compacted, cured, and subjected to vacuum desiccation or vacuum saturation as prescribed by Figure 42 (Volume 2).

e. A resilient modulus, M_R, of 200,000 psi was determined at standard condition 73°F (23°C) and at a loading rate of 0.1 seconds. This M_R was used in pavement design calculation to be discussed subsequently.

f. The following stability values were obtained in accordance with Figure 42 (Volume 2)

Marshall stability	1000 lb.
flow	0.11 in.
resistance R_t ($R_t = R + 0.05C$)	82
Moisture pick-up	2.0%

According to the criteria in Tables 36 (Volume 2) and 39 (Volume II), this emulsified asphalt stabilized soil is suitable for use as a base course.

Step 3

Figure 15 (Volume 1) summarizes the Chevron design method and was used for pavement structural design. The following summary of previously calculated data was used as input to Figure 15 (Volume 1).

Traffic data (Daily equivalent 18 kip single axle loads)	500
Subgrade CBR	10
Full cure M_R of treated mix	200,000 psi
Air voids, V_a	5%
Asphalt volume, V_b	11%*
Field cure period (from Figure 41)	1 year
Design temperature region (Table 9, Volume 1)	>65°F

*see asphalt volume calculation below.

*Asphalt Volume calculation:

$$V_b = \frac{P_b\ G_s\ (100 - V_a)}{100 \times G_b + P_b \times G_s}$$ (see Chapter I, Volume 1 for definitions)

$P_b = 7.9 \times .60$ as the emulsion contains 60% residual asphalt

$$V_b = \frac{(4.74)(2.65)[100-.05]}{(100)(1.00) + (4.74)(2.65)}$$

$V_b = 9.8\%$

a. Entering Table 10 (Volume 1) with an estimated subgrade modulus of 15,000 psi (subgrade modulus ∿ 1500 x CBR), and annual average temperature of >65°F and an equivalent axle load of 3.6×10^6 (20 years design period x 500 EAL per day x 365 days per year). A thickness of emulsified asphalt of 18 in. is interpolated.

b. No thickness correction is required because the volume of asphalt and the air voids are 10% and 5% respectively of the total mixture (Figure 17 (Volume 1).

c. For a 20-year design period, an early cure correction factor of 1.03 is selected from Table 11 (Volume 1). The emulsified asphalt thickness thus required is changed to

   1.03 x 18 in. = 18.5 in.

d. Using Tables 12 and 13 (Volume 1) to determine design thickness of emulsified asphalt to satisfy subgrade strain requirements for both early and fully cured conditions, it is readily apparent that the thickness required to satisfy tensile strain requirements controls. A thickness of 18.5 in. is more than adequate to satisfy subgrade strain requirements.

e. The total design thickness of emulsified asphalt above the subgrade is then 18.5 in. Of course, this does not account for any hot mix asphalt contrete surface. If a good quality hot mix surface were added, having an M_R of say 600,000 psi at 65°F, the average annual air temperature, the total pavement thickness to satisfy tensile strain in the asphalt layers and subgrade strain would be significantly reduced. The Asphalt Institute design procedure utilizing layer equivalencies or layered elastic analysis could be used to develop pavement structural design in this case. These methods will not be included in this example. However, for the purposes of cost and energy comparisons a pavement containing 5 in. of asphalt concrete and 12 in. of emulsion stabilized subgrade will be considered equivalent.

Step 4

From Table 20 the average representative cost of asphalt-treated base is \$0.60/yd^2-in. With asphalt concrete at a cost of \$1.00/yd^2-in., an estimated cost for the pavement is \$12.20/yd^2.

From Table 38 (Volume 1) a total energy consumption for emulsified asphalt treated base in place is 15,600 Btu/yd^2-in. With asphalt concrete utilizing 29,000 Btu/yd^2-in. an estimated energy demand for the pavement section is 332,200 Btu/yd^2.

Option 3 - Unstabilized Base and Subbase

Step 2

Suitable base and subbase materials have been located within a 100 mile haul.

Step 3

a. Pavement thickness design analysis can be performed based on information available in Volume 1, Chapter III. For a roadbed soil support value of 5, daily equivalent 18 kip single-axle loads of 500, a regional factor of 1.25 and terminal serviceability index of 2.5, a Structural Number of 3.7 is required (Volume 1, Figure 2).

b. Strength coefficients for the base and subbase materials are 0.11 and .07, respectively. Hot mixed asphalt concrete will be used as the surface material and has a coefficient of 0.44.

c. Obviously, there are many possible layer combinations to achieve a SN of 3.7. Below one alternative is shown:

$D_1 = 2$	Asphalt concrete	$a_1 = 0.44$
$D_2 = 12$	Untreated base	$a_2 = 0.11$
$D_3 = 21$	Untreated subbase	$a_3 = 0.07$

Natural subgrade

Step 4

From Table 20 (Volume 1) the average representative cost of unstabilized base and subbase is \$0.45 and \$0.35/yd^2-in., respectively. With asphalt concrete at a cost of \$1.00/yd^2-in., an estimated cost for the pavement is \$14.75/yd^2.

From Table 38 (Volume 1) a total energy consumption for untreated base and subbase are approximately 10,000 and 7,000 Btu/yd^2-in., respectively. With asphalt concrete utilizing 29,000 But/yd^2-in. an estimated energy demand for the pavement section is 325,000 Btu/yd^2.

First costs and energy demand for the three options are given below for comparison purposes:

Option	First Cost, \$/yd^2	Energy Demand Btu/yd^2
Cement Stabilization	8.10	339,000
Emulsion Stabilization	12.20	332,200
Unstabilized	14.75	325,000

It is important first cost and energy demand not be the only criteria for selection of the pavement section. Life cycle costs and energy demand should be calculated as shown in Appendices C and D of Volume 1.

DESIGN EXAMPLE 2

A county highway in southern Illinois is to be expanded from two lanes to four lanes. The natural surficial soil of the area is fine grained with a high clay content. The following data were gathered for planning and design purposes:

a. Soil reconnaissance and boring program results:

% passing No. 4 sieve	100
% passing No. 10 sieve	100
% passing No. 40 sieve	90
% passing No. 60 sieve	75
% passing No. 200 sieve	62
material smaller than 0.05 mm (silt and clay combined)	60
material smaller than 0.002 mm (clay)	40

liquid limit, Wl	55
plasticity index, PI	37
γd_{max} (natural soil), lb/ft^3	105
W_{opt}(natural soil), %	18.0
CBR	3

b. Traffic data indicates a traffic volume of 1000 daily 18 kip equivalent axle loads should be estimated for the design lane for the analysis period.

Step 1

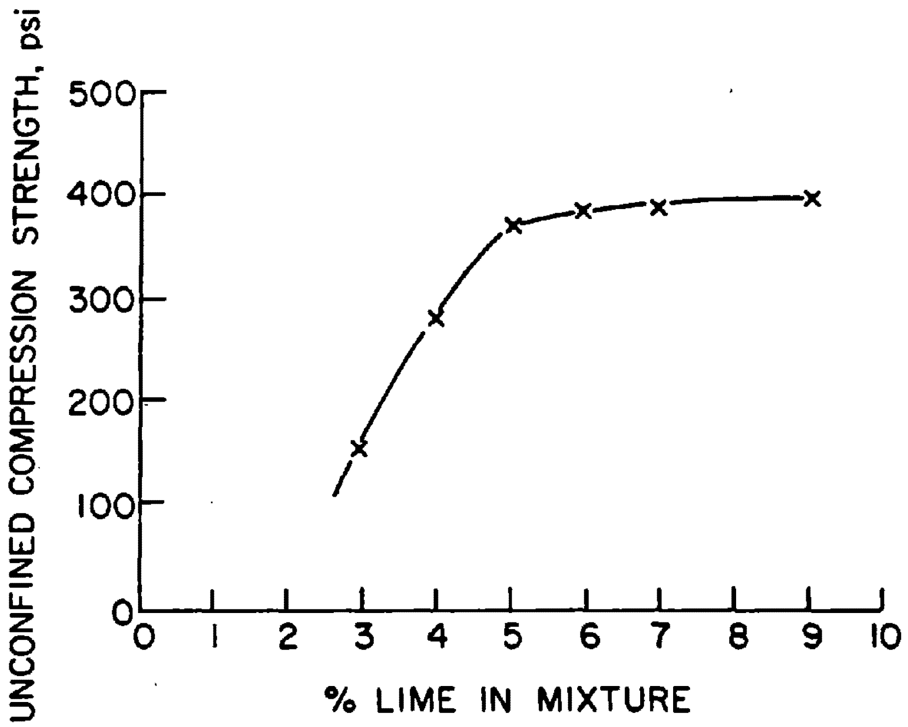
From Figure 7 of Volume 2, the best methods of stabilization of the natural soil are: (1) lime stabilization, or (2) a combination of lime to reduce the PI to <30 and then cement stabilization.

Option 1 - Lime Stabilization

Step 2

The Illinois mixture design procedures discussed in Appendix A of Volume 2 were followed.

a. Soil-lime specimens were prepared at optimum moisture content and maximum dry density (18.0% and 105 lb/ft^3 respectively) with 3, 5, 7, and 9% lime, and these specimens were tested in unconfined compression with the following results:



The addition of 3% lime yielded an unconfined compressive strength of 155 psi which is 100 psi greater than that of the natural soil. The soil was, therefore, considered lime reactive. Five percent lime was selected as the design lime content as no appreciable increase in strength is obtained for lime contents above 5 percent. To offset field variability the field design lime content was selected as 6 percent.

Step 3

Using the AASHO pavement design method, the structural layer coefficient of the lime treated subgrade was selected as 0.11.

a. The SN was computed as 5.0 from Figure 2 (Volume 1) on the basis of the following data:

soil support value = 3.0
daily equivalent 18 kip single axle load application = 1000
regional factor = 1.0

b. If 6 in. of asphalt concrete hot mix surface course is used:

D_1 = 6"	Asphalt concrete	$a_1 = 0.44$
D_2 = ?	Lime stabilized subgrade	$a_2 = 0.11$
	Subgrade SSV = 3.0	

$$SN = 5.0 = a_1D_1 + a_2D_2$$

$$= (0.44)\ (6) + (0.11)\ (D_2)$$

$$\underline{D_2 = 24 \text{ in.}}$$

c. An alternative here to avoid developing such a deep stabilized layer would be to bring in a crushed stone base:

D_1 = 6"	Asphalt concrete	$a_1 = 0.44$
D_2 = ?	Crushed stone	$a_2 = 0.15$
D_3 = 10"	Lime stabilized subbase	$a_3 = 0.11$
	Subgrade SSV = 3.0	

$$SN = 5.0 = a_1D_1 + a_2D_2 + a_3D_3$$

$$= 0.44(6) + 0.15(D_2) + 0.11(10)$$

$$\underline{D_2 = 11.4 \text{ say } 12 \text{ in.}}$$

Option 2 - Lime-Cement Stabilization

Step 2

The Atterberg limits (W_l W_p) are measured for the natural soil plus various percentages of lime (1%, 2% and 3%). It was found that the addition of 3% lime reduced the PI from 37 to 25. According to Figure 7 (Volume 2), the modified soil is now suitable for stabilization with cement.

Step 3

The natural soil was classified according to AASHO and Unified soil classification systems. The AASHO classification is A-7-6, and the Unified classification is CH. According to Figure 32 (Volume I), Table 21 (Volume 1) should be used to determine the cement content (pH test and gravimetric test indicate organics and sulfates are not a problem).

a. The cement content obtained from Table 21 (Volume 1) is 13% by weight.

b. Specimens were fabricated in accordance with ASTM procedures at 13% cement by weight and tested in freeze-thaw and wet-dry. The maximum weight losses after freeze-thaw and wet-dry analysis were as follows:

freeze-thaw test	5% weight loss
wet-dry test	3% weight loss

According to Table 22 (Volume 1) these weight losses are acceptable.

Step 4

In order to structurally evaluate the stabilized soil, laboratory tests are required to establish such properties as: (1) unconfined compressive strength, (2) flexural and tensile strength, (3) CBR, (4) resilient modulus, (5) fatigue behavior, etc. Probably this single most important strength parameter is the unconfined compressive strength as other strength parameters can often be estimated from unconfined compressive strength as a result of regression analysis.

The unconfined compressive strength of the laboratory molded mixture of lime, cement and soil at optimum moisture and γd_{max} for the mixture was 500 psi. When reduced to compensate for mixed-in-place field construction variation and field mixing efficiency, the design unconfined compressive strength become

500 (psi) (0.65) (0.75) = 244 psi.

a. Using the AASHO Interim Guide pavement design procedure, a structural layer coefficient of 0.15 was estimated for the stabilized natural soil from the guideline of Table

b. The design SN of 5.0 was established from Figure 2 (Volume 1). The following parameters were used to establish SN:

   Soil support number = 3
   18 kip daily single axle load equivalents = 1000
   Regional factor = 1.0
   Design for P_t = 2.5

c. If 6 in. of asphalt concrete hot mix is used (a_1 = 0.44) directly over the stabilized subgrade, 16 in. of stabilized subgrade are required.

D_1 = 6"	Asphalt concrete	a_1 = 0.44
D_2 = ?	Lime-cement stabilized subgrade	a_2 = 0.15
	Subgrade SSN = 3	

$$SN = 5.0 = a_1D_1 + a_2D_2$$

$$= 0.44\ (6) + 0.15\ (D_2)$$

$$\underline{D_2 = 15.7, \text{ say } 16 \text{ in.}}$$

d. An alternative here would be to use a central plant mixing operation in lieu of in-place mixing. This would improve mixing efficiency and reduce construction variation, but, unfortunately, not enough to improve the structural layer coefficient. For example, for a central plant operation,

$\left(\frac{\text{field mix strength}}{\text{lab mix strength}}\right)$ = 0.85 as opposed to 0.65 for mixed in place and the coefficient of variation is 0.15 as opposed to 0.25. Therefore the design unconfined compressive strength is

500 psi (0.85)(0.85) = <u>361 psi</u>

DESIGN EXAMPLE 3

Because of the difficulty in obtaining lime or cement in sufficient quantities for Design Example 1, it was decided to stabilize with lime-fly ash.

Step 1

The basis for design was the mix design flow diagram for lime-fly ash, Figure 21 (Volume 1).

a. The proportion of aggregate, lime and fly ash were estimated from Table 18 (Volume I) for this soil gradation as follows:

aggregate	73.5%
fly ash	22.5%
lime	4.0%

b. The fly ash was determined acceptable in terms of reactivity and gradation, ASTM.

c. The fly ash content which produced maximum dry density of the fly ash aggregate mixture was established by trial at various percentages of fly ash mixed with aggregate at 10.0% moisture. The optimum fly ash content was 25% by weight of the mixture.

d. At this proportion of aggregate to fly ash (4:1) the moisture-density analysis was performed to determine the optimum moisture content for the soil-fly ash mixture. The optimum moisture content was 11.5%.

e. All 11.5% moisture specimens were made at 25% fly ash, 28% fly ash and 22% fly ash by weight of the mixture. The maximum density occurred at a fly ash content of 25%.

f. LFA mixtures were prepared at optimum moisture content and fly ash content and at 2.5, 3, 3.5, and 4% lime. These mixtures were cured for 7 days.

g. The unconfined compressive strength was found to be 750 psi and the maximum weight loss after 12 freeze-thaw cycles was 6%. These meet the criteria established in Table 17 (Volume 1).

Step 2

Using the AASHTO pavement design method the design SN is 3.7 (see design example 1). Assuming this job to be a central plant operation rather than a mixed-in-place operation, the design unconfined compressive strength may be calculated as follows:

Central plant mixing efficiency = 0.85 of laboratory

Central plant construction variation = 0.85 of laboratory
(reference)

Design unconfined compressive strength = 750 (0.85) (0.85)

= 542 psi

A structural layer coefficient of $a_2 = 0.20$ was selected from Table 2 (Volume 1) on the basis of unconfined compressive strength of a stabilized layer. The pavement design with 6" of hot mix asphalt surface then becomes:

D_1 = 6"	Asphalt concrete	$a_1 = 0.44$
D_2 = ?	LFA stabilized	$a_2 = 0.20$
	Subgrade SSN = 5	

$$AN = 3.7 = a_1D_1 + a_2D_2$$

$$= 0.44\ (6) + 0.2\ (D_2)$$

$$\underline{D_2 = 13.2 \text{ in.}}$$

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APPENDIX A

QUALITY CONTROL

Quality control is essential to assure that the final product will be adequate for its intended use. Additionally, it must assure that the contractor has performed work in accordance with the plans and specifications, as this is a basis for payment.

This appendix attempts to identify those control factors which are most important in soil stabilization construction with lime, lime-fly ash, cement, and asphalt. Inspection and testing requirements for each of those factors will also be discussed. This discussion is in general terms and is not meant to serve as an all-inclusive guide for field personnel.

Statistical Quality Control, which is rapidly gaining acceptance, will be discussed in light of its applicability to soil stabilization construction.

Scope

Development of laboratory methods for soil stabilization will be of little value if the results of these methods cannot be successfully applied in the field. The success, at least in part, is more likely if some plan is available to assure the quality of the final product. The engineer in the field encounters highly variable conditions such as climate, efficiency of equipment and soil type. These items can be a major impact during construction. Therefore field personnel must be aware of those factors which control the quality of the final product. The use of lime, lime-fly ash, cement, and asphalt in soil stabilization can present significant problems, unless the field engineer has some familiarity with those factors which must be controlled to assure that an investment of time and money will not be wasted.

The quality of stabilized mixtures, as produced and placed, must be monitored on a continuing basis to ensure a quality product. The general tests normally conducted on these materials are listed below in their order of importance or frequency of testing.

1. In-place density (AASHTO T 238-73, AASHTO T 205-65, or AASHTO T 191-61).

2. Stabilizer content

   (lime, lime-fly ash, and cement - ASTM D 136-71)
   (Asphalt - AASHTO T 110-70, or AASHTO T 164-76)

3. Gradation (ASTM D 136-71)

4. Moisture content (ASTM D 2216-71, or AASHTO T 239-73)

In addition, frequent checks should be made on all batch and continuous feeds of mixing plants to ensure that the metering of the components is progressing uniformly.

Several general procedures important to quality control are summarized at the conclusion of this Appendix.

SOIL-LIME

Detailed procedures have been identified for soil-lime construction (1). The factors that seem most important to control during construction are:

1. Pulverization and scarification,
2. Lime content,
3. Uniformity of mixing,
4. Time sequence of operations,
5. Compaction, and
6. Curing.

Pulverization and Scarification

Prior to the application of lime, the soil is scarified or pulverized. In order to assure the adequacy of this phase of construction, a sieve analysis is performed. Most specifications are based upon a designated amount of material passing the one-inch and No. 4 sieves (48). The depth of scarification or pulverization is also of importance as it relates to the specified depth of lime treatment. For heavy clays adequate pulverization can best be achieved by pre-treatment with lime (47). A research project conducted in Iowa identified the difficulties encountered in achieving adequate pulverization and recommended the establishment of realistic gradation requirements prior to the introduction of the stabilizing agent (53). When pre-treatment with lime is utilized, it is important to recognize that agglomerated soil-lime fractions may appear (48). These fractions can be easily broken down with a simple kneading action and are not necessarily indicative of improper pulverization.

Lime Content

When lime is applied to the pulverized soil, the rate at which it is being spread can be determined by placing a canvas of known area on the ground and, after the lime has been spread, weighing the lime on the canvas (48). Charts can be made available to field personnel to determine if this rate of application is satisfactory for the lime content specified (47).

Uniformity of Mixing

Of concern here is obtaining a uniform lime content throughout the depth of treated soil. This presents one of the most difficult factors to control in the field. It has been reported that mixed soil and lime has more or less the same outward appearance as mixed soil without lime (54). The use of a phenophthalein indicator solution for control in the field has been recommended (48, 54). This method, while not sophisticated enough to provide an exact measure of lime content for depth of treatment, will give an indication of the presence of the minimum lime content required for soil treatment. The soil will turn a reddish-pink color when sprayed with the indicator solution, indicating that free lime is available in the soil (ph = 12.5) (54). Short cut methods of performing strength tests are available to determine the efficiency of the mixing (48).

Compaction

Of significance here is the proper control of moisture-density. Conventional procedures such as sand cone, rubber ballon, and nuclear methods have been used for determining the density of compacted soil lime mixtures (48, 55). Moisture content can be determined by either oven dry methods or nuclear methods (48). The influence of time between mixing and compacting has been demonstrated to have a pronounced effect on the properties of the treated soil (56). Compaction should begin as soon as possible after final mixing has been completed. The National Lime Association recommends an absolute maximum delay of one week (47). Nady and Handy have recommended the use of phenolphthalein indicator solution for lime content control testing (54). The solution can be used to distinguish between areas that have been properly treated and those that have received only a light surface dusting by the action of wind. This will aid in identifying areas where density test samples should be taken.

Curing

Curing is essential to assure that the soil lime mixture will achieve the final properties desired. Curing is accomplished by one of two methods: (1) moist curing, involving a light sprinkling of water and rolling, or (2) membrane curing, which involves sealing the compacted layer with a bituminous seal coat. Regardless of the method used, the entire compacted layer must be properly protected to ensure that the lime will not become non-reactive through carbonation. Intermittent sprinkling which allows the stabilized soil surface to dry will promote carbonation.

Other Considerations

The National Lime Association provides specifications for hydrated lime and information on storage and handling requirements (47, 57). Field personnel should assure that the lime used in the treatment process has not been rendered non-reactive through improper storage and handling.

SOIL-LIME-FLY ASH

The nature of lime-fly ash stabilization is similar to that for lime only. Consequently, the same factors involved for quality control are suggested.

SOIL-CEMENT

Detailed procedures have been identified for soil-cement construction (51). Those factors which are most important from a quality control standpoint are:

1. Pulverization,
2. Cement content,
3. Moisture content,
4. Uniformity of mixing,
5. Time sequence of operations,
6. Compaction, and
7. Curing.

Pulverization

Pulverization is generally not a problem in soil cement construction unless clayey or silty soils are being stabilized. Sieve analysis is performed on the soil during the pulverization process with the No. 4 sieve used as a control. The percent pulverization can then be determined by calculation (58). Proper moisture control is also essential in achieving the required pulverization.

Cement Content

Cement content is normally expressed on a volume or dry weight basis. Tables and graphs can be made available to field personnel which will enable them to determine quantities of cement per linear foot or per square yard of pavement (58). To assure that the proper quantity of cement is being applied, spot checks can be made by using a canvas of known area or, as an overall check, the area over which a known tonnage has been spread.

Moisture Content

The optimum moisture content determined in the laboratory is used as an initial guide when construction begins. Allowance must be made for the in-situ moisture content of the soil when construction starts. The optimum moisture content and maximum density can then be established for field control purposes. Short cut methods are available for performing field moisture density tests (58). Mixing water requirements can be determined on the raw soil or on the soil-cement mix prior to the addition of the mixing water. Graphs and tables can be made available to field personnel as an aid in determining the proper quantities of mixing water to be added (7, 58). Nuclear methods can also be used to determine moisture content at the time construction starts and during processing.

Uniformity of Mixing

To assure the uniformity of the mixture throughout the treated depth, a visual inspection is made. Uniformity must be checked across the width of the pavement and to the desired depth of treatment. Trenches can be dug and then visually inspected. A satisfactory mix will exhibit a uniform color throughout, while a streaked appearance indicates a non-uniform mix (58). Special attention should be given to the edges of the pavement.

Compaction

Equipment used for compaction is the same that would be used if no cement were present inthe soil, and is therefore dependenct upon soil type. Several methods can be utilized to determine compacted density: sand-cone method, ballon method, oil method, and nuclear method (58). It is important to determine the depth of compaction and special attention should be given to compaction at the edges.

Curing

To assure proper curing a bituminous membrane is frequently applied over large areas. The surface of the soil cement should be free of dry loose material and in a moist condition. It is important that the soil-cement mixture be kept continuously moist until the curing membrane is applied (59, 60). The recommended application rate is 0.15 to 0.30 gal. per sq. yd. (0.7 to 1.4 litres/m^2) (58).

SOIL-ASPHALT

Detailed procedures have been identified for soil-asphalt construction (52). The factors that seem most important to control during construction are:

1. Surface moisture content,
2. Viscosity of the asphalt,
3. Asphalt content,
4. Uniformity of mixing,
5. Aeration,
6. Compaction, and
7. Curing.

Surface Moisture Content

The surface moisture of the soil to be stabilized is of concern. Surface moisture can be determined by conventional methods, such as oven-drying, or by nuclear methods. The Asphalt Institute recommends a surface moisture of up to 3% or more for use with emulsified asphalt and a moisture content of less than 3% for cutback asphalt (52). The gradation of the aggregate has proven to be of significance as regards moisture content. With dense graded mixes, more water is needed for mixing than compaction (61). Generally speaking, a surface moisture content that is too high will delay compaction of the mixture. Higher plasticity index soils require higher moisture contents.

Viscosity of the Asphalt

The Asphalt Institute recommends that cold-mix construction should not be performed at temperatures below 50°F (10°C) (52). The asphalt will rapidly reach the temperature of the aggregate to which it is applied and at lower temperatures difficulty in mixing will be encountered. On occasion some heating is necessary with cutback asphalts to assure that the soil aggregate particles are thoroughly coated.

Asphalt Content

Information can be provided to field personnel which will enable them to determine a satisfactory application rate (52). The asphalt content should be maintained at optimum or slightly below for the specified mix (62). Excessive quantities of asphalt may cause difficulty in compaction and result in plastic deformation in service during hot weather.

Uniformity of Mixing

Visual inspection can be utilized to determine the uniformity of the mixture. With emulsified asphalts, a color change from brown to black indicates that the emulsion has broken (61). The Asphalt Institute recommends control of three variables to assure uniformity for mixed-in-place construction: (1) travel speed of application equipment, (2) volume of aggregate being treated, and (3) flow rate (volume per unit time) of emulsified asphalt being applied (68). In many cases, an asphalt content above design is necessary to assure uniform mixing. Studies have shown that the uniformity of the mixture can have a significant effect on the riding quality of the finished pavement (62). Research studies and practice have shown that uniformity of mixing is more easily obtained with a central plant mix operation (52, 64).

Aeration

Prior to compaction, the dilutents that facilitated the cold-mix operation must be allowed to evaporate. If the mix is not sufficiently aerated, it cannot be compacted to acceptable limits. The Asphalt Institute has determined that the mixture has sufficiently aerated when it becomes tacky and appears to "crawl" (52). Most aerating occurs during the mixing and spreading stage, but occasionally additional working on the roadbed is necessary. The Asphalt Institute has reported that overmixing in central plant mixes can cause emulsified asphalts to break early, resulting in a mix that is difficult to work in the field (63).

Compaction

Compaction should begin when the aeration of the mix is completed. The Asphalt Institute recommends that rolling begin when an emulsified asphalt mixture begins to break (color change from brown to black) (63). Early compaction can cause undue rutting or shoving of the mixture due to overstressing under the roller. The density of emulsion stabilized bases has in many cases been found to be higher than that obtained on unstabilized bases for the same compaction effort (65).

Curing

Curing presents the greatest problem in asphalt soil stabilization. The Asphalt Institute has determined that the rate of curing is dependent upon many variables: quantity of asphalt applied, prevailing humidity and wind, the amount of rain, and the ambient temperature (52). Initial curing must be allowed in order to support compaction equipment. This initial curing, the evaporation of dilutents, occurs during the aeration stage. If compaction is started too early, the pavement will be sealed, delaying dehydration, which lengthens the time before design strength is reached (61). The heat of the day may cause the mixture to soften, which prohibits equipment from placing successive lifts until the following day (64). This emphasizes the need to allow sufficient curing time when lift construction is employed. The Asphalt Institute recommends a 2- to 5-day curing period under good conditions when emulsified bases are being constructed (63). Cement has been used to accelerate curing on the construction of U.S. Forest Service Roads (61).

STATISTICAL QUALITY CONTROL

In recent years the trend towards End Result Specifications has led to the implementation of Statistical Quality Control (SQC) in highway construction. Thirty-three state highway agencies now use or plan to use some form of statistically oriented end result specifications (66). It has been stated that for absolute 100% assurance that a particular quantity of work or material is acceptable, it is necessary to inspect every unit thereof and in construction this is impractical if not impossible (67). A statistical analysis by the California Division of Highways in 1968 revelaed that the quality of work by highway contractors was as near to perfection as is economically practical (68). This would seem to question any change in quality control plans. However, the reasons for changing to SQC in highway construction given by Beaton of the California Division of Highways were: (1) the trend towards end result specifications, and (2) the increasing speed of construction (68). The latter reason seems especially valid in light of the fact that rigid "recipe type" specifications can have a significant impact on the rate at which work is performed. In a statistical quality control system, the agency monitors the contractors' quality control procedures and periodically takes samples to perform its own testing. This serves as a check on the contractor and enhances the reliability of the results.

There has been considerable discussion on the advantages and disadvantages of a statistical quality control plan (66, 67, 68). However, it has been determined in research studies that the older more acceptable "control plan" was not quite as reliable as many had thought (68).

Statistical quality control can readily be applied to soil stabilization construction. Many of the control factors discussed previously under stabilization with lime, lime-fly ash, cement, and asphalt, could be tested under the SQC method. The SQC method could be used to determine both the number of samples to be tested and the locations from which the samples should be taken. The Asphalt Institute has devised a random sampling plan for selecting sampling locations in trucks handling asphalt mixtures and for the selection of sampling locations at the paving site (52). This plan, although designed for asphalt cold-mix construction, could be utilized for other types of soil stabilization whether central mix or mixed-in-place methods are used (see summary of this method at conclusion of this appendix).

In establishing an SQC plan, it must be recognized that there are risks involved for both the buyer and the seller. The seller's risk involves the rejection of material that is good on the basis of samples that are bad. The buyer's risk involves the acceptance of material that is bad on the basis of samples that are good. One approach for determining acceptable buyer's and seller's risk is to consider the criticality of the characteristic of the material or construction for which the acceptance plan is intended (66). Acceptance plans must then be developed by the contracting agency to ensure that it receives the most satisfactory product with the fewest possible defects for the inspection effort specified.

SUMMARY AND CONCLUSIONS

There is no single source of information on the subject of quality control in the field for soil stabilization. However, numerous research studies have been conducted which provide valuable information in the quality control area.

The important control factors that have been identified for soil stabilization with lime, lime-fly ash, cement, and asphalt are essentially the same for each material. However, it must be recognized that the inherent properties of these materials are dissimilar and therefore the behavior of the mateirals in the field will be quite different. It is important that field personnel be familiar with the distinct properties of each material. It would be advantageous to field personnel to be provided with as much information as possible by the design engineers. Plans and specifications alone are not always adequate. In many instances, problems in the field are a result of inadequate communication between design and field engineers.

Statistical quality control can be quite adaptable to soil stabilization construction. Considering the control factors that have been identified, SQC could be utilized to determine the number and location of tests such as density, moisture content, sieve analysis, etc. Given the variable behavior of lime, lime-fly ash, cement, and asphalt in the field, it is not felt that simply specifying the end result would be satisfactory. However, a modification of the end result specification could be employed. For example, it might be possible to specify pulverization requriements, lime content, and final density. This would allow the contractor to be more innovative in performing the construction.

Statistical quality control should not be viewed as a "panacea" for quality control problems in the field. It should be used by field personnel as an aid to judgment which will assist them in making decisions on the basis of conditions at a given time during construction.

With the implementation of a statistical quality control plan, it is important that the contracting agencies establish "realistic" acceptance specifications. Specifications that are particularly stringent will inhibit the realization of the benefits associated with SQC. Further, rigid specifications will result in higher costs and this is an important consideration in soil stabilization, which is a low-cost construction method. Therefore it is questionable whether a highly sophisticated and stringent quality control effort should be specified. If inspection costs are excessive, then the method of construction should be reevaluated. In this regard, it is felt that Statistical Quality Control can provide a final product which will be adequate for its intended use and at the same time testing and inspecting requirements will be economical.

Useful Tests

A. Rapid Test Method for Soil-Lime Construction to determine the efficiency of mixing (48):

(a) Secure a sample of the field mixed soil-lime material,
(b) Halve the sample,
(c) Prepare strength specimens (unconfined compression) from one portion,
(d) Completely "remix" the other portion of the field mixture to ensure almost 100% mixing,
(e) Prepare strength specimens from the "remixed material",
(f) Cure both samples and test, and
(g) Calculate mixing efficiency as follows:

$$\% = \frac{\text{Field mixed strength}}{\text{Lab mixed strength}} \times 100$$

(For mixed-in-place, expect 60-80%).

B. Determination of percent pulverization for soil cement construction (58):

$$\% = \frac{\begin{array}{l}\text{Dry Weight of Soil Cement Mixture}\\ \text{Passing the No. 4 Sieve}\end{array}}{\begin{array}{l}\text{Dry Weight of the Total Sample}\\ \text{Exclusive of Gravel Retained on}\\ \text{the No. 4 Sieve}\end{array}} \times 100$$

To improve pulverization (58)

(1) Slower forward speed of mixing machine,
(2) Additional passes, if using multiple pass mixer,
(3) Replaceing worn mixing teeth, and
(4) Prewetting and pre-mixing the soil before processing begins.

C. Short cut method of moisture density test (58):

(a) Obtain field sample near optimum moisture,
(b) Split sample in three parts,
(c) Use one portion to establish a point near the peak of the moisture density curve,
(d) Add a small increment of water to a second portion to obtain

a point on the wet side of the curve, and
(e) Third portion, which has dried slightly, used to obtain a point on the dry side of the moisture-density curve.

Factors to Consider in Statistical Quality Control

A. Classification of Criticality (66):

1. Critical - The defect will make the product dangerous to use,
2. Major - This defect will seriously impair performance of the item,
3. Minor - This defect may impair performance, but not seriously, and
4. Contractual - This defect is likely to have insignificant effect on performance.

B. Acceptable Buyer's and Seller's Risks (66):

Classification Characteristic	Buyer's Risk	Seller's Risk
Critical	0.5	5.0
Major	5.0	1.0
Minor	10.0	0.5
Contractual	20.0	0.1

C. Essential Elements of a Complete, Statistically Oriented Lot Acceptance Plan (66):

1. Specifications should define the size of the lot in terms of appropriate units of measure such as tons, square yards, or linear feet of lane,

2. The point of sampling should be stated,

3. The method of random sampling should be stated,

4. The number of samples to be taken or the number of measurements to be made on each lot or sublot should be stated,

5. The method of test (AASHTO, ASTM, or agency) by which the material or construction will be evaluated should be stated,

6. The target or desired value of the measured characteristic of the material or construction should be stated. In many cases this would be the Job-Mix-Formula (JMF) value,

7. Realistic tolerances should be placed on the target value and where acceptance is based on average values:

$$JMF \pm \left[\frac{2\sigma}{\sqrt{n}} + d\right]$$

σ = Std. Dev.
n = No. of samples
d = Allowance for target miss

8. The action to be taken in case the material or construction does not fully comply with the specified quality requirements given.

D. Contracting Agency Acceptance Procedures (66):

1. Types of Acceptance Plans:

a. Attributes Sampling Plan - Visual inspection is all that is required and
b. Variable Sampling Plan - Characteristics can be measured.

Variable Acceptance Plan:

1. Standard deviation known,

$L \leq \overline{X}_n \leq U$ (Eq. 2)

$\overline{X}_n \leq JMF + k\sigma$ (Eq. 3a)

$\overline{X}_n \geq JMF - k\sigma$ (Eq. 3b)

L = lower acceptance limit
U = upper acceptance limit
JMF = job mix formula
$\overline{X}_n$ = average of a small group of measurements
k = probability factor
σ = Std. deviation (assumed to be known from a large number of measurements)

2. Standard deviation unknown.

$(\overline{X}_n - L) \geq ks$ (Eq. 5a)

$(U - \overline{X}_n) \geq ks$ (Eq. 5b)

L or U = a specified limit
$\overline{X}_n$ = average of a small group of measurements
s = standard deviation of the small group of measurements
k = factor that determines statistical probability of acceptance

Random Sampling Plans*

Selecting Sampling Locations in Trucks Hauling Asphalt Mixture (Procedure No. 1)--The following definitions apply (see also Figure 52):

- o Lot - a quantity of material that one desires to control. It may represent a day's production, a specified tonnage, a specified number of truckloads, a specified time period during production.
- o Sample - a segment of a lot chosen to represent the total lot. It may represent any number of subsamples.
- o Subsample - a segment of a sample, taken from a unit of the lot, i.e., a specified ton, a specified time, a specified truckloads, and
- o Sample Unit - a portion of subsample taken from a unit of a lot and combined with one or more other sample units to make up a subsample.

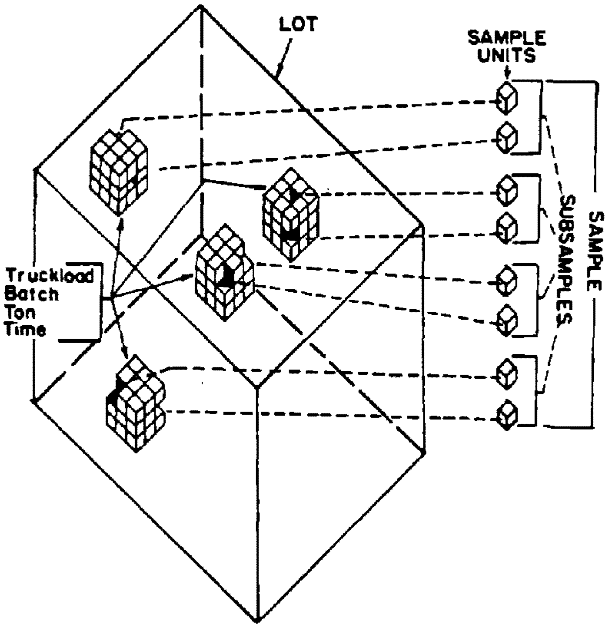

Figure 52. Schematic diagram illustrating lot, sample, subsample, and sample unit.

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*Source: The Asphalt Institute, "Asphalt Cold-Mix Manual," Manual Series No. 14, February, 1974 (52).

In this procedure the following steps are necessary to select the sampling locations:

(1) Select the lot size - it can be time (hours), an average day's production (tons), a selected tonnage (example: 2,000 tons), or a selected number of truckloads. A lot size of a day's production is recommended for this procedures as being convenient and easy to randomize.

(2) Select the number of samples desired per lot. One sample per lot, made up of four subsamples, is the minimum recommended.

(3) Select the number of locations in each truckload from which sampling units of asphalt mixtures will be taken to combine into one subsample. Two sampling units per subsample are recommended.

(4) Assign each truckload of mixture in the lot a number, beginning with 1 for the first truckload and number them successively to the highest number in the lot. Find the truckload numbers for sampling by the following procedure:

- o Place consecutively numbered 1 through x one-inch (25 mm) square pieces of cardboard, equal to the number of truckloads (x) in the lot, into a container (such as a bowl). Mix them thoroughly before each drawing.
- o Draw a number of cardboard squares from the container equal to the number of subsamples desired for the lot. The numerals on the cardboard squares will be the truckloads to be sampled, and

(5) Choose for each subsample desired the location in the truckload for each of the sampling units. Use the following steps:

- o Divide the truck beds into equal quadrants and number them 1 through 4 in any order desired.
- o Place four consecutively numbered (1 through 4) one-inch (25 mm) square pieces of cardboard into a container (such as a bowl). Mix them thoroughly before each drawing.
- o Draw out an amount of cardboard squares equal to the number of sample units desired. The numerals on each square drawn represent the quadrants from which the sample unit will be taken. Replace the cardboard squares and repeat this step for each sample unit of each subsample to be taken.

Selecting Sampling Locations at Pavement Site (Procedure No. 2)--Table 15 contains random numbers for the general sampling procedure. To use this table for selecting locations for sampling or testing, the

Table 15. Random Number for General Sampling Procedure.

COL. NO. 1			COL. NO. 2			COL. NO. 3			COL. NO. 4			COL. NO. 5			COL. NO. 6			COL. NO. 7		
A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
15	.033	.576	05	.048	.879	21	.013	.220	18	.089	.716	17	.024	.863	30	.030	.901	12	.029	.386
21	.101	.300	17	.074	.156	30	.036	.853	10	.102	.330	24	.060	.032	21	.096	.198	18	.112	.284
23	.129	.916	18	.102	.191	10	.052	.746	14	.111	.925	26	.074	.639	10	.100	.161	20	.114	.848
30	.158	.434	06	.105	.257	25	.061	.954	28	.127	.840	07	.167	.512	29	.133	.388	03	.121	.656
24	.177	.397	28	.179	.447	29	.062	.507	24	.132	.271	28	.194	.776	24	.138	.062	13	.178	.640
11	.202	.271	26	.187	.844	18	.087	.887	19	.285	.899	03	.219	.166	20	.168	.564	72	.209	.421
16	.204	.012	04	.188	.482	24	.105	.849	01	.326	.037	29	.264	.284	22	.232	.953	16	.221	.311
08	.208	.418	02	.208	.577	07	.139	.159	30	.334	.938	11	.282	.262	14	.259	.217	29	.235	.356
19	.211	.798	03	.214	.402	01	.175	.641	22	.405	.295	14	.379	.994	01	.275	.195	28	.264	.941
29	.233	.070	07	.245	.080	23	.196	.873	05	.421	.282	13	.394	.405	06	.277	.475	11	.287	.199
07	.260	.073	15	.248	.831	26	.240	.981	13	.451	.212	06	.410	.157	02	.296	.497	02	.336	.992
17	.262	.308	29	.261	.087	14	.255	.374	02	.461	.023	15	.438	.700	27	.311	.144	15	.393	.488
25	.271	.180	30	.302	.883	06	.310	.043	06	.487	.539	22	.453	.635	05	.351	.141	19	.437	.655
06	.302	.672	21	.318	.088	11	.316	.653	08	.497	.396	21	.472	.824	17	.370	.811	24	.466	.773
01	.409	.406	11	.376	.936	13	.324	.585	25	.503	.893	05	.488	.118	09	.388	.484	14	.531	.014
13	.507	.693	14	.430	.814	12	.351	.275	15	.594	.603	01	.525	.222	04	.410	.073	09	.562	.678
02	.575	.654	27	.438	.676	20	.371	.535	27	.620	.894	12	.561	.980	25	.471	.530	06	.601	.675
18	.591	.318	08	.467	.205	08	.409	.495	21	.629	.841	08	.652	.508	13	.486	.779	10	.612	.859
20	.610	.821	09	.474	.138	16	.445	.740	17	.691	.583	18	.668	.271	15	.515	.867	26	.673	.112
12	.631	.597	10	.492	.474	03	.494	.929	09	.708	.689	30	.736	.634	23	.567	.798	23	.738	.770
27	.651	.281	13	.499	.892	27	.543	.387	07	.709	.012	02	.763	.253	11	.618	.502	21	.753	.614
04	.661	.953	19	.511	.520	17	.625	.171	11	.714	.049	23	.804	.140	28	.636	.148	30	.758	.851
22	.692	.089	23	.591	.770	02	.699	.073	23	.720	.695	25	.828	.425	27	.650	.741	27	.765	.563
05	.779	.346	20	.604	.730	19	.702	.934	03	.748	.413	10	.843	.627	16	.711	.508	07	.780	.534
09	.787	.173	24	.654	.330	22	.816	.802	20	.781	.603	16	.858	.849	19	.778	.812	04	.818	.187
10	.818	.837	12	.728	.523	04	.838	.166	26	.830	.384	04	.903	.327	07	.804	.675	17	.837	.353
14	.985	.631	16	.753	.344	15	.904	.116	04	.843	.002	09	.912	.382	08	.806	.952	05	.854	.818
26	.912	.376	01	.806	.134	28	.969	.742	12	.884	.582	27	.935	.162	18	.841	.414	01	.867	.133
28	.920	.163	22	.878	.884	09	.974	.046	29	.926	.700	20	.970	.582	12	.918	.114	08	.915	.538
03	.945	.140	25	.939	.162	05	.977	.494	16	.951	.601	19	.975	.327	03	.992	.399	25	.975	.584

COL. NO. 8			COL. NO. 9			COL. NO. 10			COL. NO. 11			COL. NO. 12			COL. NO. 13			COL. NO. 14		
A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
09	.042	.071	14	.061	.935	26	.038	.023	27	.074	.779	16	.073	.987	03	.033	.091	26	.035	.175
17	.141	.411	02	.065	.097	30	.066	.371	06	.084	.396	23	.078	.056	07	.047	.391	17	.089	.363
02	.143	.221	03	.094	.228	27	.073	.876	24	.098	.524	17	.096	.076	28	.064	.113	10	.149	.681
05	.162	.899	16	.122	.945	09	.095	.568	10	.133	.919	04	.153	.163	12	.066	.360	28	.238	.075
03	.285	.016	18	.158	.430	05	.180	.741	15	.187	.079	10	.254	.834	26	.076	.552	13	.244	.767
28	.291	.034	25	.193	.469	12	.200	.851	17	.227	.767	06	.284	.628	30	.087	.101	24	.262	.366
08	.369	.557	24	.224	.572	13	.259	.327	20	.236	.571	12	.305	.616	02	.127	.187	08	.264	.651
01	.436	.386	10	.225	.223	21	.264	.681	01	.245	.988	25	.319	.901	06	.144	.068	18	.285	.311
20	.450	.289	09	.233	.838	17	.283	.645	04	.317	.291	01	.320	.212	25	.202	.674	02	.340	.131
18	.455	.789	20	.290	.120	23	.363	.063	29	.350	.911	08	.416	.372	01	.247	.025	29	.353	.478
23	.488	.715	01	.297	.242	20	.364	.366	26	.380	.104	13	.432	.556	23	.253	.323	06	.359	.270
14	.498	.276	11	.337	.760	16	.395	.363	28	.425	.864	02	.489	.827	24	.320	.651	30	.387	.248
15	.503	.342	19	.389	.064	02	.423	.540	22	.487	.526	29	.503	.787	10	.328	.365	14	.392	.694
04	.515	.693	13	.411	.474	08	.432	.736	05	.552	.511	15	.518	.717	27	.338	.412	03	.408	.077
16	.532	.112	20	.447	.893	10	.476	.468	14	.564	.357	28	.524	.998	13	.356	.991	27	.440	.280
22	.557	.357	22	.478	.321	03	.508	.774	11	.572	.306	03	.542	.352	16	.401	.792	22	.461	.830
11	.559	.620	29	.481	.993	01	.601	.417	21	.594	.197	19	.585	.462	17	.423	.117	16	.527	.003
12	.650	.216	27	.562	.403	22	.687	.917	09	.607	.524	05	.695	.111	21	.481	.838	30	.531	.486
21	.572	.320	04	.566	.179	29	.697	.862	19	.650	.572	07	.733	.838	08	.560	.401	25	.678	.360
13	.709	.273	08	.603	.758	11	.701	.605	18	.664	.101	11	.744	.948	19	.564	.190	21	.725	.014
07	.745	.687	15	.632	.927	07	.728	.498	25	.674	.428	18	.793	.748	05	.571	.054	05	.797	.595
30	.780	.285	06	.707	.107	14	.745	.679	02	.697	.674	27	.802	.967	18	.587	.584	15	.801	.927
19	.845	.097	28	.737	.161	24	.819	.444	03	.767	.928	21	.826	.487	15	.604	.145	12	.836	.294
26	.846	.366	17	.846	.130	15	.840	.823	16	.809	.529	24	.835	.832	11	.641	.298	04	.854	.982
29	.861	.307	07	.874	.491	25	.863	.568	30	.838	.294	26	.855	.142	22	.672	.156	11	.884	.928
25	.906	.874	05	.880	.828	06	.878	.215	13	.845	.470	14	.861	.462	20	.674	.887	19	.886	.832
24	.919	.809	23	.931	.659	18	.930	.601	08	.855	.524	20	.874	.625	14	.752	.881	07	.929	.932
10	.952	.555	26	.960	.365	04	.954	.827	07	.867	.718	30	.929	.056	09	.774	.560	09	.932	.206
06	.961	.504	21	.978	.194	28	.963	.004	12	.881	.722	09	.935	.582	29	.921	.752	01	.970	.692
27	.969	.811	12	.982	.183	19	.988	.020	23	.937	.872	22	.947	.797	04	.959	.099	23	.973	.082

Table 15. Random Number for General Sampling Procedure (Continued).

COL. NO. 15			COL. NO. 16			COL. NO. 17			COL. NO. 18			COL. NO. 19			COL. NO. 20			COL. NO. 21		
A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
15	.023	.979	19	.062	.588	13	.045	.004	25	.027	.290	12	.052	.075	20	.030	.881	01	.010	.946
11	.118	.465	25	.080	.218	18	.086	.878	06	.057	.571	30	.075	.493	12	.034	.291	10	.014	.939
07	.134	.172	09	.131	.295	26	.126	.990	26	.059	.026	28	.120	.341	22	.043	.893	09	.032	.346
01	.139	.230	18	.136	.381	12	.128	.661	07	.105	.176	27	.145	.689	28	.143	.073	06	.093	.180
16	.145	.122	05	.147	.864	30	.146	.337	18	.107	.358	02	.209	.957	03	.150	.937	15	.151	.012
20	.165	.520	12	.158	.365	05	.169	.470	22	.128	.827	26	.272	.818	04	.154	.867	16	.185	.455
06	.185	.481	28	.214	.184	21	.244	.433	23	.156	.440	22	.299	.317	19	.158	.359	07	.227	.277
09	.211	.316	14	.215	.757	23	.270	.849	15	.171	.157	18	.306	.475	29	.304	.615	02	.304	.400
14	.248	.348	13	.224	.846	25	.274	.407	08	.220	.097	20	.311	.653	06	.369	.633	30	.316	.074
25	.249	.890	15	.227	.809	10	.290	.925	20	.252	.066	15	.348	.156	18	.390	.536	18	.328	.799
13	.252	.577	11	.280	.898	01	.323	.490	04	.268	.576	16	.381	.710	17	.403	.392	20	.352	.288
30	.273	.088	01	.331	.925	24	.352	.291	14	.275	.302	01	.411	.607	23	.404	.182	26	.371	.216
18	.277	.689	10	.399	.992	15	.361	.155	11	.297	.589	13	.417	.715	01	.415	.457	19	.448	.754
22	.372	.958	30	.417	.787	29	.374	.882	01	.358	.305	21	.472	.484	07	.437	.696	13	.487	.598
10	.461	.075	08	.439	.921	08	.432	.139	09	.412	.089	04	.478	.885	24	.446	.546	12	.546	.640
28	.519	.536	20	.472	.484	04	.467	.266	16	.429	.834	25	.479	.080	26	.485	.768	24	.550	.038
17	.520	.090	24	.498	.712	22	.508	.880	10	.491	.203	11	.566	.104	15	.511	.313	03	.604	.780
03	.523	.519	04	.516	.396	27	.632	.191	28	.542	.306	10	.576	.659	10	.517	.290	22	.621	.930
26	.573	.502	03	.548	.688	16	.661	.836	12	.563	.091	29	.665	.397	30	.556	.853	21	.629	.154
19	.634	.206	23	.597	.508	19	.675	.629	02	.593	.321	19	.739	.298	25	.561	.837	11	.634	.908
24	.635	.810	21	.681	.114	14	.680	.890	30	.692	.198	14	.749	.759	09	.574	.599	05	.696	.459
21	.679	.841	02	.739	.298	28	.714	.508	19	.705	.445	08	.756	.919	13	.613	.762	23	.710	.078
27	.712	.366	29	.792	.038	06	.719	.441	24	.709	.717	07	.798	.183	11	.698	.783	29	.726	.585
05	.780	.497	22	.829	.324	09	.735	.040	13	.820	.739	23	.834	.647	14	.715	.179	17	.749	.916
23	.861	.106	17	.834	.647	17	.741	.906	05	.848	.866	06	.837	.978	16	.770	.128	04	.802	.186
12	.865	.377	16	.909	.608	11	.747	.205	27	.867	.633	03	.849	.964	08	.815	.385	14	.835	.319
29	.882	.635	06	.914	.420	20	.850	.047	03	.883	.333	24	.851	.109	05	.872	.490	08	.870	.546
08	.902	.020	27	.958	.856	02	.859	.356	17	.900	.443	05	.859	.935	21	.885	.999	28	.871	.539
04	.951	.482	26	.981	.976	07	.870	.612	21	.914	.483	17	.863	.220	02	.958	.177	25	.971	.369
02	.977	.172	07	.983	.624	03	.916	.463	29	.950	.753	09	.863	.147	27	.961	.980	27	.984	.252

COL. NO. 22			COL. NO. 23			COL. NO. 24			COL. NO. 25			COL. NO. 26			COL. NO. 27			COL. NO. 28		
A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
12	.051	.032	26	.051	.187	08	.015	.521	02	.039	.005	16	.026	.102	21	.050	.952	29	.042	.039
11	.068	.980	03	.053	.256	16	.068	.994	16	.061	.599	01	.033	.886	17	.085	.403	07	.105	.293
17	.089	.309	29	.100	.159	11	.118	.400	26	.068	.054	04	.088	.686	10	.141	.624	25	.115	.420
01	.091	.371	13	.102	.465	21	.124	.565	11	.073	.812	22	.090	.602	05	.154	.157	09	.126	.612
10	.100	.709	24	.110	.316	18	.153	.158	07	.123	.649	13	.114	.614	06	.164	.841	10	.205	.144
30	.121	.744	18	.114	.300	17	.190	.159	05	.126	.658	20	.136	.576	07	.197	.013	03	.210	.054
02	.166	.056	11	.123	.208	26	.192	.676	14	.161	.189	05	.138	.228	16	.215	.363	23	.234	.533
23	.179	.529	09	.138	.182	01	.237	.030	18	.166	.040	10	.216	.565	08	.222	.520	13	.266	.799
21	.187	.051	06	.194	.115	12	.283	.077	28	.248	.171	02	.233	.610	13	.269	.477	20	.305	.603
22	.205	.543	22	.234	.480	03	.286	.318	06	.255	.117	07	.278	.357	02	.288	.012	05	.372	.223
28	.230	.688	20	.274	.107	10	.317	.734	15	.261	.928	30	.405	.273	25	.333	.633	26	.385	.111
19	.243	.001	21	.331	.292	05	.337	.844	10	.301	.811	06	.421	.807	28	.348	.710	30	.422	.315
27	.267	.990	08	.346	.085	25	.441	.336	24	.363	.025	12	.426	.583	20	.362	.961	17	.453	.783
15	.283	.440	27	.382	.979	27	.469	.786	22	.378	.792	08	.471	.708	14	.511	.989	02	.460	.916
16	.352	.089	07	.387	.865	24	.473	.237	27	.379	.959	18	.473	.738	26	.540	.903	27	.461	.841
03	.377	.648	28	.411	.776	20	.475	.761	19	.420	.557	19	.510	.207	27	.587	.643	14	.483	.095
06	.397	.769	16	.444	.999	06	.557	.001	21	.467	.943	03	.512	.329	12	.603	.745	12	.507	.375
09	.409	.428	04	.515	.993	07	.610	.238	17	.494	.225	15	.640	.329	29	.619	.895	28	.509	.748
14	.465	.406	17	.518	.827	09	.617	.041	09	.620	.081	09	.665	.354	23	.623	.333	21	.583	.804
13	.499	.651	05	.539	.620	13	.641	.648	30	.623	.106	14	.680	.884	22	.624	.076	22	.587	.993
04	.539	.972	02	.623	.271	22	.664	.291	03	.625	.777	26	.703	.622	18	.670	.904	16	.689	.339
18	.560	.747	30	.637	.374	04	.668	.856	08	.651	.790	29	.739	.394	11	.711	.253	06	.727	.298
26	.575	.892	14	.714	.364	19	.717	.232	12	.715	.599	25	.759	.386	01	.790	.392	04	.731	.814
29	.756	.712	15	.730	.107	02	.776	.504	23	.782	.093	24	.803	.602	04	.813	.611	08	.807	.983
20	.760	.920	19	.771	.552	29	.727	.548	20	.810	.371	27	.842	.491	19	.843	.732	15	.833	.757
05	.847	.925	23	.780	.662	14	.823	.223	01	.841	.726	21	.870	.435	03	.844	.511	19	.896	.464
25	.872	.891	10	.924	.888	23	.848	.264	29	.862	.009	28	.906	.367	30	.858	.299	18	.916	.384
24	.874	.135	12	.929	.204	30	.892	.817	25	.891	.873	23	.948	.367	09	.929	.199	01	.948	.610
08	.911	.215	01	.937	.714	28	.943	.190	04	.917	.264	11	.956	.142	24	.931	.263	11	.976	.799
07	.946	.065	25	.974	.398	15	.975	.962	13	.958	.990	17	.993	.989	15	.939	.947	24	.978	.633

following steps are necessary:

(1) For compacted pavement sampling or testing locations, use each day's run as a separate section,

(2) Determine the number of sampling locations within a section by selecting the maximum average longitudinal distance desired between samples and dividing the length of the section by the maximum average longitudinal distance,

(3) Select a column of random numbers in Table 15 by placing 28 one-inch (25 mm) square pieces of cardboard, numbered 1 through 28, into a container (such as a bowl), shaking them to get them thoroughly mixed, and drawing one out,

(4) Go to the column of random numbers identified with the number drawn from the container. In sub-column A, locate all numbers equal to and less than the number of sampling locations per section desired,

(5) Multiply the total length of the section by the decimal values in sub-column B, found opposite the numbers located in sub-column A. Add the result to the station number at the beginning of the section to obtain the station of the sampling location, and

(6) Multiply the total width of the proposed pavement in the section by the decimal values in sub-column C, found opposite the numbers located in sub-column A, then subtract one-half the total width of the proposed pavement from the result to obtain the offset distance from the centerline to the sampling location. A positive (+) number will be the distance to the right of centerline and a negative (-) number will be the distance to the left of centerline. If only one lane of pavement is involved, the total width will be the lane width and the offset distance will be measured from the left edge of the lane.

APPENDIX B

GUIDE SPECIFICIATIONS

As discussed in each of the principal chapters for different stabilizers, there are many similarities in construction methods. Each materials chapter has pointed out the requirements for stabilizer quality and mixture design. The methodology for evaluation of soils and binders and their optimum proportioning is an important part of the design process. Similarly, the construction requirements for each type of stabilization covered in this manual are discussed in Chapter VIII. There are somewhat different needs for mixing, curing, etc., for each stabilizer and these should be carefully noted.

During the design stage of a given project, the owner agency must also prepare plans, write specifications, prepare contract proposals, as well as other concerns about how the project will be constructed. The owner must be concerned with several major aspects of the project, including:

1. General description of the project,
2. Materials to be used,
3. Special equipment that may be required,
4. Construction methods to be employed including mixing, placement, compaction, and curing, and
5. Quality control/quality assurance with regard to sampling, testing, and method of measurement or payment.

In addition to the broader aspects of the project above, the owner agency must establish limits or criteria for quality. Laboratory evaluations coupled with experience and such factors as local climate and soil materials will strongly influence these criteria. Many agencies have already standardized specifications for most conventional road construction and these should be used wherever possible. Often, a specification that is currently in force may be modified slightly to accomplish the guidance of construction. Other instances, particularly when a soil stabilization procedure is new to the agency, will require the development of entirely new and perhaps unique specifications.

The intent of this Appendix is to illustrate the major factors to be considered in developing specifications for stabilizing pavement layers. It would be impractical to attempt complete coverage of the subject; therefore, a selection of three examples are included to aid the engineer in preparing his own. Those included are:

1. Lime-fly ash-aggregate stabilization for base and subbase courses,
2. Roadmixed asphalt stabilized base and surface courses, and
3. Travel plant for asphalt base treatment.

In addition to those above, many agencies have developed specifications and special provisions for soil stabilization. A listing of some of those currently in use that may be helpful are presented below:

1. AASHTO - Guide Specifications for Highway Construction, 1968,
2. U.S. Department of Transportation (FAA) 150/5370A "Standard Specifications for Construction of Airports," 1968,
3. U.S. Corps of Engineers "Engineering and Design Manual - Soil Stabilization for Roads and Streets," 1969,
4. National Lime Association, "Lime Stabilization Construction," Bulletin 326, 1972,
5. Asphalt Institute, "Asphalt Cold Mix Manual," Manual Series No. 14, 1977,
6. Portland Cement Association, "Soil Cement Construction Handbook," (EB003S); Soil-Cement Inspector's Manual," (PA050S),
7. Portland Cement Association, "Suggested Specifications for Soil-Cement Base Course," (IS008S),
8. American Road and Transportation Builders Association, "Materials for Stabilization," 1977,
9. Chevron, U.S.A., Inc., "Bitumuls Mix Manual," 1977,
10. Asphalt Institute, "Model Construction Specifications for Asphalt Concrete and Other Plant Mix Types," Specification Series SS-1, 1975,
11. Transportation Research Board, "State of the Art: Lime Stabilization," Circular No. 180, 1976,
12. Federal Highway Administration, "Fly Ash A Highway Construction Material," Implementation Package No. 76-16, 1976, and
13. Many state highway agency Standard Specifications.

APPENDIX B-1

TYPICAL SPECIFICATIONS FOR LIME-FLY ASH--AGGREGATE BASE/SUBBASE COURSE*

1. Description

1.1 This item shall consist of constructing a base course by mixing, spreading, shaping, and compacting mineral aggregate, lime, fly ash, and water. It shall be placed on the prepared underlying course in accordance with the requirements of this specification and shall conform to the dimensions and typical cross sections shown on the plans and to the lines and grades established by the engineer.

2. Materials

2.1 Lime-Fly Ash Cementitious Filler Material. The lime and fly ash shall be supplied either separately or as a manufactured blend. The lime, fly ash, or blend may contain admixtures such as water-reducing agents, portland cement, or other materials that are known to provide supplementary properties to the final mix. When admixtures are to be included, they are to be used in the laboratory mixture selection process.

The lime shall meet ASTM Specification C 207, Type N, sections 2 and 3(a) when sampled and tested in accordance with sections 6 and 7. The fly ash shall meet ASTM Specification C 593, section 3.2, when sampled and tested in accordance with sections 4, 6, and 8. The water-soluble fraction shall not be determined. The preceding requirements may be waived if it is demonstrated that a mix of comparable quality and reliability can be produced with lime and/or fly ash that do not meet these criteria. If portland cement is blended with either lime or fly ash, or both, or added at the mixer, it shall be a standard brand and shall conform to the requirements specified in AASHTO M 85 for the type specified.

2.2 Water. The water for the base course shall be clean, clear, and free from injurious amounts of sewage, oil, acid, strong alkalies, or vegetable matter, and it shall be free from clay or silt. If the water is of questionable quality, it shall be tested in accordance with the requirements of AASHTO T 26. Water known to be of potable quality may be used without tests.

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*Source: NCHRP, "Lime-Fly Ash--Stabilized Based and Subbases," Synthesis of Highway Practice Report No. 37, 1976 (23).

2.3 Aggregate. The aggregate may be either stone, gravel, slag, or sand, crushed or uncrushed, or any combination thereof. In addition to the fine aggregate naturally contained in the coarse material, supplementary fly ash may be used as a mineral filler to provide the desired fines content.

The crushed or uncrushed mass shall consist of hard, durable particles of accepted quality (crushed if necessary to reduce the largest particles to the largest accepted size and free from an excess of flat, elongated, soft, or disintegrated pieces, or dirt or other deleterious materials.

The methods used in processing such as crushing, screening, blending, and so forth, shall be such that the finished product shall be as consistent as practicable. If necessary to meet this requirement or to eliminate an excess of fine particles, the materials shall be screened before and during processing, and all stones, rock, boulders, and other source material of inferior quality shall be wasted.

The aggregate shall show no evidence of general disintegration nor show a total loss of more than 12 percent when subjected to five cycles of the sodium sulfate accelerated soundness test specified in AASHTO T 104; however, if an aggregate source that fails to meet this requirement can show an acceptable performance record in service, it may be accepted.

All material passing the No. 4 (4.75 mm) sieve and produced during crushing or other processing may be incorporated in the base material to the extent permitted by the gradation requirements, unless it is known to contain significant deleterious material.

A wide range of aggregate gradations are permitted with these base materials provided appropriate mixture proportion procedures are followed. If the maximum particle size in the aggregate exceeds 0.75 in. (19 mm), the aggregate shall meet the gradation requirements given in Table 53 when tested in accordance with AASHTO T 11 and T 27.

The gradation in the table sets limits that shall determine the general suitability of the aggregate from a source of supply. The final gradations selected for use shall be within the limits designated in the table, and shall also be well graded from fine to coarse and shall not vary from high to low limits on subsequent sieves.

In addition to the gradations given in Table 16, clean sands and sand-sized materials, such as boiler slags, can be used. Also, if the aggregate has a substantial portion (75 percent) passing the No. 4 (4.75 mm) mesh sieve the gradations in Table 16 can be waived and the aggregate gradation adjusted with the fly ash and fines contents to produce the maximum dry density in the compacted mixture.

Table 16. Requirements for Gradation of Aggregate for the Plant-Mix Base Course

Sieve designation (aquare openings)		Percentage by weight passing sieves		
		A	B	C
2 inch	(50 mm)	100	-	-
1-1/2 inch	(38.1 mm)	-	100	-
1 inch	(25 mm)	55-85	70-95	100
3/4 inch	(19 mm)	50-80	55-85	70-100
No. 4	(4.75 mm)	40-60	40-60	40-65
No. 40	(425 µm)	10-30	10-30	15-30
No. 200	(75 µm)	5-15	5-15	5-15

Table 17. Bituminous Curing Materials for LFA Bases

Type and Grade	Specification	Application Temperature, F (C)
Curback asphalt MC-30	AASHTO M82	120-150 (49-65)
Emulsified asphalt	Fed. Spec. SS-A-674	75-130 (23-54)

The portion of the base material including any blended material passing the No. 40 (425 µm) mesh sieve shall have a liquid limit of less than 25 and a plasticity index of less than 6 when tested in accordance with AASHTO T 89 abd T 90.

2.4 Bituminous Material. The types,grades, controlling specifications, and application temperatures for the bituminous materials used for curing the lime-fly ash-aggregate-treated base course are given in Table 17. The engineer shall designate the specific material to be used.

3. Laboratory Tests and Lime-Fly Ash Content

3.1 Lime Content. The quantity of lime (approximately 2 to 5 percent by weight) to be used with the aggregate, fly ash, and water, shall be determined by tests for the materials submitted by the contractor, at his own expense, and in a manner satisfactory to the engineer.

3.2 Fly Ash Content. The quantity of fly ash (approximately 9 to 15 percent by weight) to be used with the aggregate, lime, and water shall be determined by tests for the materials submitted by the contractor, at his own expense, and in a manner satisfactory to the engineer.

3.3 Manufactured Blend Content. The quantity of manufactured blend to be used with the aggregate and water (and any supplemental fly ash) shall be determined by tests for the materials submitted by the contractor, at his own expense, and in a manner satisfactory to the engineer.

3.4 Laboratory Tests. Specimens of the lime-fly ash-aggregate base course material shall develop a minimum compressive strength of 400 psi (2700 kPa) and demonstrate freeze-thaw resistance of a maximum of 14 percent weight loss as specified in ASTM Specification C 593, section 3.2, when tested in accordance with section 9 of that specification except that all compaction shall be done in accordance with FAA T 611, section 2.2(a) and (b).

4. Construction Methods

4.1 Sources of Supply. All work involved in clearing and stripping pits, including handling unsuitable material, shall be performed by the contractor. All costs involved in clearing and stripping pits, including labor, equipment, and other incidentals shall be included in the price of the material. The contractor shall notify the engineer sufficiently in advance of the opening of any designated pit to permit staking of boundaries at the site, to take elevations and measurements of the ground surface before any material is produced, to permit the engineer to take samples of the material for tests to determine its quality and gradation, and to prepare a preliminary base mixture proportion. All materials shall be obtained from approved sources.

The pits, as used, shall be opened immediately to expose vertical faces of the various strata of acceptable material and, unless otherwise directed, the material shall be secured in successive vertical cuts extending through all the exposed strata in order to secure a uniform material.

4.2 Equipment. All methods employed in performing the work and all equipment, tools, other plans and machinery used for handling materials and executing any part of the work shall be subject to the approval of the engineer before the work is started. If unsatisfactory equipment is found, it shall be changed and improved. All equipment, tools, machinery, and plants must be maintained in a satisfactory working condition.

4.3 Preparing Underlying Course. The underlying course shall be checked and accepted by the engineer before placing and spreading operations are started. Any ruts or soft, yielding places caused by improper drainage conditions, hauling, or any other cause, shall be corrected and rolled to the required compaction before the base course is placed thereon.

Grade control between the edges of the pavement shall be accomplished by grade stakes, steel pins, or forms placed in lanes parallel to the centerline of the runway and at intervals sufficiently close that string lines or check boards may be placed between the stakes, pins, or forms.

To protect the underlying course and to ensure proper drainage, the spreading of the base shall begin along the centerline of the pavement on a crowned section or on the high side of the pavement with one-way slope.

4.4 Mixing

4.4.1. General requirements. Lime-fly ash-treated base shall be mixed at a central mixing plant by either batch or continuous mixing. The capacity of the mixing plant should not be less than 50 tons per hour (45 metric tons per hour). The aggregates, lime, and fly ash may be proportioned either by weight or by volume.

In all plants, water shall be proportioned by weight or volume, and there shall be means by which the engineer may readily verify the amount of water per batch or the rate of flow for continuous mixing. The discharge of the water into the mixer shall not be started before part of the aggregates are placed into the mixer. The inside of the mixer shall be kept free from any hardened mix.

In all plants, lime and fly ash (and portland cement when used in the mix) shall be added in such a manner that they are uniformly distributed throughout the aggregates during the mixing operation.

The charge in a batch mixer, or the rate of feed into a continuous mixer shall not exceed that which will permit complete mixing of all the material. Dead areas in the mixer, in which the material does not move or is not sufficiently agitated, shall be corrected either by a reduction in the volume of material or by other adjustments.

4.4.2 Batch Mixing. In addition to the general requirements as provided in Sec. 4.4.1, batch mixing of the materials shall conform to the following requirements:

- o The mixer shall be equipped with a sufficient number of paddles of a type and arrangement to produce a uniformly mixed batch,
- o The mixer platform shall be of ample size to provide safe and convenient access to the mixer and other equipment. The mixer and batch-box housing shall be provided with hinged gates of ample size to permit easy sampling of the discharge of aggregate from each of the plant bins and of the mixture from each end of the mixer,

- The continuous feeder for the aggregate may be mechanically driven or electrically driven. Aggregate feeders that are mechanically driven shall be directly connected with the drive on the lime feeder, and

- The pugmill for the continuous mixer shall be equipped with a surge hopper containing sufficient baffles and gates to prevent segregation of material discharged into the truck and to allow for closing of the hopper between trucks without requiring shutdown of the plant.

4.5 Placing, Spreading, and Compacting. The use of mixers having a chute delivery shall not be permitted except as approved. In all such cases the arrangement of chutes, baffle plates, etc., shall ensure the placing of the lime-fly ash-treated base without segregation.

The prepared underlying course shall be free of all ruts or soft yielding places. The surface, if dry, shall be moistened but not to an extent that causes a muddy condition at the time the base mixture is placed.

Any dusting or surface ravelling caused by traffic on the sealed base course material shall be the responsibility of the contractor and shall be taken care of as directed by the engineer.

4.6 Construction Joints. The protection provided for construction joints shall permit the placing, spreading, and compacting of base material without injury to the work previously laid. Care shall be exercised to ensure thorough compaction of the base material immediately adjacent to all construction joints.

4.7 Protection and Curing. After the base course has been finished as specified herein, it shall be protected against drying until the surface course is applied by the application of bituminous material or other acceptable methods, such as frequent light applications of water by a pressure water distributor. A double seal shall be used for the small projects where a surface course layer is not required.

The bituminous material specified shall be uniformly applied to the surface of the completed base course at the rate of approximately 0.15 gallons per square yard (0.68 litre per square metre) using approved heating and distributing equipment. The exact rate and temperature of application to give complete coverage without excessive runoff shall be as directed by the engineer. At the time the bituminous material is applied, the surface shall be dense, free of all loose and extraneous material, and shall contain sufficient moisture to prevent penetration of the bituminous material. All surfaces shall be cleaned of all dust and unsound materials to the satisfaction of the engineer. Cleaning shall be done with rotary brooms and/or blowing the surface with compressed air, with the surface reasonably moistened to prevent air

- The mixer shall be equipped with a timing device that will indicate by a definite audible or visual signal the expiration of the mixing period. The device shall be accurate to within two seconds. The plant shall be equipped with an automatic device suitable for counting the number of batches.

- The mixing time of a batch shall begin after all ingredients are in the mixer and shall end when the mixer is half emptied. Mixing shall continue until a homogeneous mixture of uniformly distributed and properly coated aggregates of unchanging appearance is produced. In general, the time of mixing shall be not less than 30 seconds; however, the time may be reduced when tests indicate that the requirements for lime-fly ash content and for compressive strength can be consistently met.

4.2.2.1 Weight Proportioning. When weight proportioning is used, the discharge gate of the weight box shall be arranged to blend the different aggregates as they enter the mixer.

4.2.2.2 Volumetric Proportioning. When volumetric proportioning is used for batch mixing, the volumetric proportioning device for the aggregate shall be equipped with separate bins, adjustable in size, for the various sizes of aggregates. Each bin shall have an accurately controlled gate or other device designed so that each bin shall be completely filled and accurately struck-off in measuring the volume of aggregate to be used in the mix. Means shall be provided for accurately calibrating the amount of material in each measuring bin.

4.4.3 Continuous Mixing. In addition to the general requirements as provided in Sec. 4.4.1, continuous mixing of the materials shall conform to the following requirements:

- The correct proportions of each aggregate size introduced into the mixer shall be drawn from the storage bins by a continuous feeder, which will supply the correct amount of aggregate in proportion to the lime-fly ash and will be arranged so that the proportion of each material can be separately adjusted. The bins shall be equipped with a vibrating unit, which will effectively vibrate the side walls of the bins and prevent any "hang up" of material while the plant is operating. A positive signal system shall be provided to indicate the level of material in each bin, and as the level of material in any one bin approaches the strike-off capacity of the feed gate, the device shall automatically and instantly close down the plant. The plant shall not be permitted to operate unless this automatic signal is in good working condition.

- The drive shaft on the aggregate feeder shall be equipped with a revolution counter accurate to 1/100 of a revolution and of sufficient capacity to register the total number of revolutions in a day's run.

pollution. Water shall be applied in sufficient quantity to fill the surface voids immediately before the bituminous curing material is applied.

Should it be necessary for construction equipment or other traffic to use the bituminous-covered surface before the bituminous material has dried sufficiently to prevent pickup, sufficient granular cover shall be applied before such use.

No traffic shall be allowed on the pozzolan base course other than that developing from the operation of essential construction equipment unless otherwise directed by the engineer. Any defects that may develop in the construction of the base course or any other damage caused by the operation of the job equipment is the responsibility of the contractor and shall be immediately repaired or replaced at no expense to the sponsor.

Other curing materials, such as moist straw or hay, may be used upon approval. Upon completion of the curing period, the straw shall be removed and disposed of as directed by the engineer.

Trucks for transporting the mixed base material shall be provided with protective covers. The material shall be spread on the prepared underlying course to such depth that, when thoroughly compacted, it will conform to the grade and dimensions shown on the plans. No time limit is required for placing the base material; however, it is suggested that the base material be placed within several hours to avoid the necessity of replacing moisture that may be lost.

The materials shall be spread by a spreader box, self-propelled spreading machine, or other method approved by the engineer. It shall not be placed in piles or windrows without the approval of the engineer. If spreader boxes or other spreading machines are used that do not spread the material the full width of the lane or the width being placed in one construction operation, care shall be taken to join the previous pass with the last pass of the spreading machine. The machine shall be moved back approximately every 600 ft (180 m) when staggered spreading machines are not used. The first pass shall not be compacted to the edge and, if necessary, the loose material shall be dampened just prior to joining the next pass. When portland cement is used in the mixture, if the temperature is 70°F (21°C) or more, the materials must be spread within four hours and reworked into the adjacent material. When portland cement is used in the mixture, and the temperature is less than 70°F (21°C), the materials must be spread within eight hours and worked into the adjacent material. Additional moisture may be required during the reworking operations as directed by the engineer.

The equipment and methods employed in spreading the base material shall ensure accuracy and uniformity of depth and width. If conditions arise where such uniformity in the spreading cannot be obtained, the

the engineer may require additional equipment or modification in the spreading procedure to obtain satisfactory results. Spreading equipment shall be no more than 30 ft (90 m) nor less than 9 ft (2.7 m) in width unless approved by the engineer.

After spreading, the material shall be thoroughly compacted by rolling. The rolling shall progress gradually from one side toward previously placed material by lapping uniformly each preceding rear-wheel track by one-half the width of such track. Rolling shall continue until the entire area of the course has been rolled by the rear wheels. The rolling shall continue until the material is thoroughly compacted, the interstices of the material reduced to a minimum, and until creeping of the material ahead of the roller is no longer visible. Rolling shall continue until the base material has been compacted to not less than 97 percent density, as determined by the compaction-control tests specified in ASTM C 593. Blading and rolling shall be done alternately, as required or directed, to obtain a smooth, even, and uniformly compacted base. Finishing operations shall continue until the surface is true to the specified cross section and until the surface shows no variations of more than 0.38 in. (9.5 mm) from a 16-ft (4.9-m) straightedge laid in any location parallel with, or at right angles to, the longitudinal axis of the pavement.

4.8 Cold Weather Protection. During cold weather if the air temperature unexpectedly drops below 35°F (1°C) and remains there for a period of several days or more, the completed base course shall be protected from freezing by any approved method if required by the engineer prior to application of the bituminous surface course. Any light surface frost caused by overnight below-freezing temperatures shall be treated by rolling the surface with a light steel-wheel roller as directed by the engineer.

4.9 Thickness. The thickness of the base course shall be determined from measurements of cores drilled from the finished base or from thickness measurements at holes drilled in the base at intervals so that each test shall represent no more than 300 square yards (250 square metres). The average core thickness shall be the thickness shown on the plans, except that if any one thickness shown by the measurements made in one day's construction is not within the tolerance given, the engineer shall evaluate the area and determine if, in his opinion, that section shall be reconstructed at the contractor's expense or the deficiency is to be deducted from the total material in place.

5. Methods of Measurements

5.1 The quantity of one course, lime-fly ash-treated base, to be paid for will be determined by measurement of the number of square yards of base actually constructed and accepted by the engineer as complying with the plans and specifications.

6. Basis of Payment

6.1 Payment shall be made at the contract unit price per square yard for lime-fly ash base course. This price shall be full compensation for furnishing all materials and for all preparation, manipulation, and placing of these materials and for all labor, equipment, tools, and incidentals necessary to complete the item.

7. Testing and Material Requirements

Test and short title:

AASHTO T 26 - Water
AASHTO T 96 - Abrasion
AASHTO T 104 - Soundness
AASHTO T 11 and T 27 - Gradation
AASHTO T 89 - Liquid Limit
AASHTO T 90 - Plastic Limit and Plasticity Index
AASHTO T 136 - Freeze-Thaw Compressive Strength

Material and short title:

ASTM C 207 - Lime
ASTM C 593 - Fly Ash
AASHTO M 85 - Portland Cement, ASTM C 150
AASHTO M 134 - Air-Entrained Portland Cement, ASTM C 226
AASHTO M 82 - Asphalt MC, ASTM D2027
AASHTO M140 and M208 - Asphalt Emulsion, ASTM D977 and D2397

APPENDIX B-2

TYPICAL SPECIFICATION FOR ROAD-MIXED ASPHALT FOR BASE AND SURFACE COURSES*

Scope

Furnish and construct mixed-in-place sand- or soil-asphalt courses as specified.

1. General Requirements

1.1 Preparation of Roadway. This type of construction may be performed either with the natural material occurring in the roadbed or by importing materials from pits or other sources.

When the material to be treated is that already in the roadbed, it shall be scarified with approved equipment to a depth 2 in. (50 mm) greater than the specified depth of pavement to be constructed and to a width 2 ft (0.6 m) outside the proposed edge of the pavement. After the material has been scarified it shall be thoroughly mixed and processed. All foreign substances shall be removed and discarded. Any particles of aggregate or agglomerations of aggregate that will not pass a 2 in. (50 mm) square opening screen shall be removed and discarded. If needed, imported material, meeting the requirements of Article B.33, shall be thoroughly mixed with the in-place material.

1.2 Equipment. As many as necessary of the following named pieces of equipment shall be used to complete the specified work: scarifiers; pulverizing equipment; rotary mixers or travel plants, motor graders; windrow devices; aggregate spreaders; power brooms or power blowers, or both; self-propelled vibratory or steel-tired tandem and pneumatic-tired rollers capable of attaining the required density; a pressure distributor designed and operated to distribute the asphaltic material in a uniform spray without atomization; equipment for heating the asphaltic material; and a water distributor. Other equipment may be used in addition to, or in lieu of, the specified equipment when approved by the engineer.

1.3 Samples. Samples of all materials proposed for use shall be submitted by the contractor to the engineer. If any portion of the in-place road materials are to be used in the construction the engineer will furnish the contractor with the test results and improvement requirements, if any, for the in-place materials. Samples of all other materials proposed for use under these specifications shall be submitted

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*Source: The Asphalt Institute, "Asphalt Cold Mix Manual," Manual Series No. 14, 1977 (52).

to the engineer for test and analysis. The material shall not be used until it is approved by the engineer.

Sampling of asphaltic materials shall be in accordance with the latest revision of AASHTO Designation T 40 (ASTM Designation D140). Sampling of mineral aggregate shall be in accordance with the latest revision of AASHTO Designation T 2 (ASTM Designation D 75).

1.4 Methods of Testing.

(1) Asphaltic materials will be tested by the methods of test of the American Association of State Highway and Transportation Officials (AASHTO). If an AASHTO method of test is not available, the American Society for Testing and Materials (ASTM) method will be used.

(2) Mineral aggregates will be tested, as designated in the detailed requirements of these specifications, by one or more of the following methods of test of the American Association of State Highway and Transportation Officials (AASHTO). If an AASHTO method of test is not available, the American Society for Testing and Materials (ASTM) method will be used.

Characteristic	Method of Test	
	AASHTO	ASTM
Sieve Analysis, Fine and Coarse Aggregates	T27	C136
Unit Weight of Aggregate	T19	C29
Sand Equivalent	T176	D2419
Plasticity Index of Soils	T90	D424

1.5 Weather. Asphalt shall not be applied to the aggregate when the air temperature in the shade is less than 50°F (10°C) unless otherwise permitted by the engineer. Work shall be suspended during rain or when the mix is wet.

1.6 Traffic Control. Traffic shall be directed through the project with warning signs, flagmen, and pilot trucks or cars in a manner that provides maximum safety for the workmen and traffic and the least interruption of the work.

Traffic shall be kept off of freshly sprayed asphalt or mixed materials.

If it is necessary to route traffic over the new work, speed shall be restricted to 25 miles/hr (40 km/hr) or less until rolling is completed and the asphalt mixture is firm enough to take high speed traffic.

1.7 Safety. Safety precautions shall be used at all times during the progress of the work. As appropriate, workmen shall be furnished with hard hats, safety shoes, asbestos gloves, repirators, and any other safety apparel that will reduce the possibility of accidents and minimize health hazards. All Occupational Safety and Health Act requirements shall be observed.

1.8 Method of Measurement. The quantities, as applicable, to be paid for will be as follows:

(1) Preparation of surface - Total number of square yards (square metres) of surface actually prepared for covering by the asphalt treatment,

(2) Asphaltic Materials - Total number of gallons (litres) at 60°F (15°C) or tons (tonnes) of each asphaltic material incorporated into the work,

(3) Mineral Aggregate - Total number of tons (tonnes) of mineral aggregate incorporated in the work,

(4) Mixing and Placing - Total number of square yards (square metres) to specified depth of road mix laid, and

(5) Water - Total number of gallons (litres) of water incorporated into the work.

1.9 Basis of Payment. The quantities described above in Secl. 1.8 will be paid for at the contract unit price bid for each item. Payment will be in full compensation for furnishing, hauling and placing materials for mixing, for rolling and for all labor and use of equipment, tools, and incidentals necessary to complete the work in accordance with these specifications.

In adjusting volumes of asphaltic material to the temperature of 60°F (15°C) ASTM Designation D 1250, ASTM-IP Petroleum Measurement Tables, will be used.

2. Materials

2.1 Asphalt Binder. The asphalt will be specified by the engineer from the following table prior to letting the contract.

Asphalt	AASHTO Specs.	ASTM Specs.
SS-1, SS-1h	M140	D977
CSS-1, CSS-1h	M208	D2397
RC-70, RC-250, RC-800	M81	D2028
MC-70, MC-250, MC-800	M82	D2027

The engineer will specify the temperature at which the material shall be used.

2.2 Mineral Aggregate. The mineral aggregate shall consist of material naturally occurring in the roadbed; material imported from local pits or other sources, with or without mineral filler; or any combination of these aggregates that will meet the following requirements:

(1) Passing a 75 μm (No. 200) U.S. Standard Sieve, not more than 25 percent.

(2) Sand Equivalent, not less than 30, or Plasticity Index, not more than 6.

3. Construction

Methods of Mixing

3.1 Preparation of Mineral Aggregate. Where mixing of the aggregate is to be done by means other than a travel mixer, any mineral filler or other aggregate to be blended with the natural material shall be spread over the surface of the scarified material in a uniform quantity, and in such quantity as will provide a mixture meeting the requirements of Sec. 2.2. Such applications shall be made immediately after the scarifying operations; mixing with a rotary-type mixer shall continue until a uniform mixture is obtained.

Where a travel mixer is to be used, the prepared in-place material shall be bladed into one or more windrows suitable for the type of travel mixer. Any additional aggregate required to be blended with the windrowed material shall be uniformly distributed over the windrows as directed by the engineer. Windrows shall contain sufficient material to produce the required thickness of compacted pavement.

If all aggregate material is to be imported from local pits or other sources, this shall be spread on the prepared subgrade or placed in windrows (depending on the method of mixing that will be used) in quantities sufficient to produce the required pavement thickness.

Alternative No. 1--Travel Mixing

3.2 Application of Asphalt (Alternative No. 1). Asphalt shall not be applied when the moisture content of the aggregate material exceeds 3 percent, unless laboratory tests indicate that a moisture content in excess of 3 percent at the time the asphalt is added will not be harmful. If the travel mixer is not equipped to measure and apply the asphalt during the mixing operation, the asphalt shall be applied directly on the measured windrows with the asphalt distributor. When the travel mixer is equipped to measure and apply the asphalt the application will be made during the mixing process.

When the travel mixer is equipped to measure and apply the asphalt, the asphalt shall be carefully heated, if needed, by means of heating coils in tanks designed to provide uniform heating of the entire contents. The contractor shall provide all necessary facilities for determining asphalt temperature during heating and prior to use, and shall take all usual precautions incidental to handling these materials.

3.3 Mixing Operation (Alternative No. 1). The aggregate material and asphalt shall be thoroughly mixed until the asphalt is uniformly distributed throughout and all aggregate particles are completely coated. The mixture shall be placed in a windrow for later spreading, aeration, and compaction.

Alternative No. 2--Blade Mixing

3.4 Application of Asphalt (Alternative No. 2). When the aggregate material is to be mixed with a motor grader, the windrow shall be flattened and the asphalt applied from a distributor. Asphalt shall not be applied when the moisture content of the aggregate exceeds 3 percent, unless laboratory tests indicate that a moisture content in excess of 3 percent at the time the asphalt is added will not be harmful.

The asphalt shall be applied uniformly upon the layer of aggregate material at the rate of 0.50 to 0.75 gal/yd^2 (2.3 to 3.5 litres/m^2) the specified temperature. The asphalt shall then be initially mixed into the layer. Successive applications of asphalt shall then be applied and mixed in quantities not exceeding 0.75 gal/yd^2(3.5 litres/m^2).

3.5 Mixing Operation (Alternative No. 2). As soon as the total specified amount of asphalt is applied to the aggregate material, mixing shall be continued with motor graders until a thorough uniform mixture is produced.

3.6 Aeration. Regardless of the mixing method used, manipulation of the mix shall continue until volatiles or water, or both, are removed in quantity sufficient to provide a compactable mix.

When mixing and aerating are complete, the mix may be laid and compacted in accordance with Sec. 3.7, or it may be placed in windrows along the edges of the area to be paved for laydown at a later time.

3.7 Spreading and Compaction. After the material has been aerated it shall be spread to a uniform grade and cross-section and compacted with a pneumatic-tired roller for the full width of the roadway. Rolling shall continue until the entire depth is compacted to the specified density. Test holes shall be dug at specified intervals to determine the compacted thickness of the layers being placed. Areas in which a deficiency of more than 13 mm (1/2 in.) compacted thickness is indicated shall be reworked with added mixed material sufficient to increase the layer to the depth specified. All irregularities that develop in the surface shall be corrected by blading while the pavement is still soft. Blading and compaction shall continue until the surface is true to grade and cross-section.

3.8 Application of Seal Coat. Upon the thoroughly-cured asphalt course, emulsified asphalt or cutback asphalt, RS-1, RS-2, CRS-1, or CRS-2, RC-250, or RC-800, shall be applied uniformly at the rate of 0.10 to 0.15 gal/yd^2 (0.45 to 0.68 litres/m^2). The asphalt shall be covered immediately with Size No. 9* aggregate at the rate of 10 to 15 lb/yd^2 (5.5 to 8 kg/m^2). The procedure for this operation shall be in accordance with Specification ST-1, Asphalt Surface Treatments (MS-13), The Asphalt Institute.

Notes to the Engineer

The foregoing specifications for road-mixed asphalt courses are recommended for use under what may be termed average conditions. It is realized, however, that no single standard specification will cover satisfactorily all variations in local conditions which may prevail for individual jobs. Before adopting these specifications verbatim the engineer, therefore, should give particular attention to the items listed below and, if necessary, make the changes suggested.

Asphalt-sand and asphalt-soil mixed-in-place courses are usually laid to a compacted thickness of from 3 to 6 in. (75 to 150 mm) depending upon traffic conditions. However, greater thicknesses may sometimes be advisable.

Prior to letting the contract the engineer should select the particular asphaltic material he wishes to use, deleting the requirements

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*See AASHTO Designation M 43.

for all other asphaltic materials shown in these specifications.

Asphalt-sand or soil mixes normally serve better as base courses. But in some localities, because of lack of aggregate and in the interest of economy, they may be used as surface courses.

The loose grading requirement in Sec.2.2 is included in this specification to allow the use of local sands and soils that may vary widely in grading but are still suitable for mixing with asphalt.

APPENDIX B-3

TYPICAL SPECIFICATION FOR TRAVEL PLANT MIX BITUMULS BASE TREATMENT*

1. Description

Travel plant mix bitumuls base treatment is a cold mixed, cold laid base course mixture of mixing asphalt and suitable aggregate used for highways, streets, roads, airport runways, parking areas, storage yards and similar paved areas. The aggregate may be any non-cohesive inert material meeting the specified gradation and test criteria. These base course aggregates are mixed by the travel plant and are then either laid down in a continuous windrow for spreading or are continuously spread out mechanically into a uniform, level mat. The travel plant meters and proportions the aggregate and the emulsion in a confined pug mill mixer. The travel plant may be either of two general types: one type mechanically picks up the aggregate from a prepared windrow; the other type is fed by dumping the aggregate (by dump truck) directly into the receiving hopper of the travel plant.

From an air quality and environmental point of view, Bitumuls travel plant mixes have been very satisfactory. There is a minimum of noise, dust, smoke or fumes generated because the paving mixture is produced from aggregates which are damp or moist and, therefore, almost dustless. The emulsified asphalt for the cold travel plant paving mixtures is not hot enough to create any objectionable odors, fumes, or smoke. For small rural or scattered projects, travel plants, such as the Moto-Paver, or the Midland Mixer-Paver, seem well adapted.

2. Materials

2.1 Aggregate may be any suitable sand, blast furnace slag, coral, volcanic cinder, gravel, ore tailings, crushed ledge stone or rock, or other inert mineral meeting the gradation, stability and test criteria outlined in Table 18.

2.2 Asphalt. The class, type, and grade of emulsified asphalt selected shall meet the requirement as specified in Table 19.

3. Requirements for the Mixture

3.1 Test Criteria. The asphalt mixture shall meet the following test criteria when tested in the laboratory:

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*Source: Chevron U.S.A., Inc., "Bitumuls Mix Manual," 1977 (22).

Table 18. Aggregate Suitable for Treatment with Bitumuls Emulsified Asphalts in Travel Plants

CATEGORY	ASTM TEST METHOD	PROCESSED* DENSE GRADED AGGREGATES	POORLY GRADED	WELL GRADED	SILTY SANDS	SEMI-PROCESSED CRUSHER, PIT OR BANK RUN AGGREGATES	PROCESSED COMMERCIAL AGGREGATE (1)
Gradation:							
1 1/2"	C-136	100				100	100
% Passing:							
1"		90-100				80-100	80-100
3/4"		65-90				-	-
1/2"		-	100	100	100	-	-
* 4		30-60	75-100	75-100	75-100	25-85	-
16		15-30	-	35-75	-	-	-
50		7-25	-	15-30	-	-	-
100		5-18	-	-	15-65	-	0-3
200		4-12	0-12	5-12	12-25	3-15	0-1
Sand Equivalent, %	D-2419	30 Min.	30 Min.	30 Min.	30 Min.	30 Min.	-
Plasticity Index	D-424	-	NP	NP	NP	-	-
Untreated Resistance R Value	T-190	78 Min.	60 Min.	60 Min.	60 Min.	60 Min.	-
Loss L.A. Rattler (500 Revolutions)	T-96	50 Max.	-	-	-	60 Max.	40 Max.

*Must have at least 65% by weight crushed particles.

(1) Notes:

(a) The Processed Commercial Aggregate shown in Table 55 is normally a graded aggregate with essentially no material passing the No. 200 sieve and having a nominal top size of 3/4". (For example, ASTM sizes 6, 7, or 8 or combinations of these sizes would be a suitable grading.)

(b) Normally when the graded processed commercial aggregate with substantially no material passing the No. 200 sieve is used in the travel plant, the emulsion selected will be the coarse mixing, CH-h or CM-Kh grades.

1 in. = 2.54×10^{-2} m

Table 19. Chevron Asphalt Company Product Specifications for Bitumuls Emulsified Asphalt Mixing Grades*

BITUMULS CLASS				ANIONIC				CATIONIC					
BITUMULS GRADE DESIGNATION				CM-h		DM-h		CM-Kh		SM-Kh		DM-Kh	
ASTM GRADE DESIGNATION (CLOSEST)				(MS-2h)		(SS-1h)		(CMS-2h)		(CMS-2h)		(CSS-1h)	
	TEST METHOD			MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
	AASHO	ASTM	CHEVRON										
Test on Emulsion (a)													
Vis. Saybolt Furol--77°F (25°C) sec.	T-59	D244	-	-	-	-	100	-	-	-	-	-	100
Vis. Saybolt Furol--122°F (50°C) sec.	T-59	D244	-	-	500	-	-	-	500	-	500	-	-
Storage Stability Test, 1 day, %	-	D244		-	1.0	-	1.0	-	1.0	-	1.0	-	1.0
Aggr. Coating--Water Resistance Test													
Dry Std. Ref. Aggr., % coated, min.	-		C-5	80	-	-	-	80	-	-	-	-	-
Wet Std. Ref. Aggr., % coated, min.	-		C-5	60	-	-	-	60	-	-	-	-	-
Cement Mixing Test, %	T-59	D244	-	-	-	-	2.0	-	-	-	-	-	2.0
Sieve Test, %	T-59	D244	-	-	0.10	-	0.10	-	0.1	-	0.1	-	0.1
Particle Charge Test (b)	T-59	D244	-	Negative		Negative		Positive		Positive		Positive	
pH (b)	T-200	E70	-	-	-	7.3	-	-	-	-	-	-	6.7
Dehydration, ratio	-		B-15	-	-	0.5	-	-	-	-	-	0.7	-
Adhesion	-		S-4	-	-	Pass	-	-	-	-	-	Pass	-
Residue by Distillation, %	T-59	D-244		60	-	57	-	65	-	60	-	57	-
Oil distillate, vol. emulsion, %	T-59	D-244		5	15	-	-	5	15	-	20	-	-
Tests on Residue from Distillation Test													
Penetration at 77°F, 100 gm, 5 sec.	T-49	D5	-	40	100	40	100	60	110	60	150	60	110
Ductility at 77°F, cm.	T-51	D113	-	40	-	40	-	40	-	40	-	40	-
Solubility in Trichloroethylene, %	T-44	D2042	-	97	-	97	-	97	-	97	-	97	-

a) All tests shall be performed within 30 days from the date of emulsified asphalt shipment.
b) Must meet pH Test if inconclusive Particle Charge Test.
* These specification requirements may vary in different locations dependent on local construction practices, aggregates, and climatic conditions. Please check with your nearest Chevron Asphalt Company District Office for grades available in your area.

Design Requirements

Test Property	Method of Test	Test Requirements
Moisture Pickup during Moisture Vapor Susceptibility Test, %	67B-307**	5.0 Max.
Resistance R_t Value $R_t = (R + 0.05\ C)$	67B-307**	
(a) For Light & Medium Traffic (DTN under 100)*		70 Min.***
(b) For Heavy to Very Heavy Traffic (DTN over 100)*		78 Min.***

*The Asphalt Institute Thickness Design Manual (MS-1).

**Chevron Asphalt Company Test Method.

***Should the sampled aggregate mixture fail to meet the requirements, it will be acceptable--if by the addition of an acceptable admixture the specified minimum Resistance R_t Value is developed. The admixture such as lime, cement, mineral filler, etc., should be economically available near the job site.

4. Equipment

4.1 Travel Plant. Travel plant shall preferably be of the twin shaft pug mill type. The travel plant continuous mixers may be one of the following types:

(1) Pick-up Type--Self-loading by pickup from windrows measured, sized, and laid out ahead on the grade.

(2) Dump-Fed Type--Dump truck supplied into receiving hopper, self-propelled, equipped with spreading augers and screed strike-off mechanisms (for example, the Moto-Paver, or the Midland Mixer-Paver).

The Dump-Fed type travel plant shall be equipped with a hopper for receiving aggregate from standard dump trucks. The travel plant shall be equipped with a conveyor and aggregate metering device for maintaining a uniform regulated flow of aggregate to the mixing chamber. The travel plant shall have a twin shaft continuous type pug mill mixer with adequate power and capacity for mixing approximately two tons or more per minute. The machine shall have one or more emulsion tanks with a minimum total capacity of approximately one thousand gallons and shall be equipped with suitable devices (burners and flues) for heating the emulsified asphalt. There shall be a dial thermometer in the emulsion line to mixing chamber having a range of 50°F to 300°F (10 to 150°C). The machine shall be equipped with a suitable variable capacity positive displacement pump, piping, and control devices for maintaining a uniform regulated flow of asphalt mixture to the mixing chamber and suitable piping and valve arrangement to permit recirculation, loading and unloading of the mixture. There shall be a mechanical electrical or hydraulic (or other suitable) interlock between the drive of the aggregate metering conveyor feed belt and the asphalt metering pump. It shall be equipped with a suitable variable capacity positive displacement pump, piping, and control devices for maintaining a uniform regulated flow of Bitumuls Emulsified Asphalt to the mixing chamber and suitable piping and valve arrangement to permit recirculation, loading and unloading of the Bitumuls Emulsified Asphalt. There shall be a mechanical electrical or hydraulic (or other suitable) interlock between the drive of the aggregate metering conveyor feed belt and the asphalt metering pump. It shall be equipped with adjustable width screed and with lateral spreading devices for maintaining adequate mixture directly in front of the strike-off screed. The screed shall be readily adjustable vertically. The travel plant shall be equipped with a gallons-per-minute indicator and a totalizing meter on the emulsion line to the mixing chamber. The aggregate regulating devices and the emulsion metering devices shall be so designed that the percentage of emulsion in the mix can be varied within a range of from four to ten percent of the aggregate by weight.

4.2 Spreading Equipment. Suitable spreading equipment must be on the project for use following those travel plants (Pick-up type) which deposit the base mixture into a windrow rather than into a full width mat ready for immediate compaction. The spreading equipment must be capable of laying out the windrowed mixture to the proper uncompacted crown, cross section and profile to produce a uniform compacted thickness as specified.

4.3 Compaction Equipment. The compacting equipment shall be of the standard steel wheel, pneumatic tire, or vibratory steel wheel types meeting the minimum requirements of the following tables:

Roller Type	Three Wheel	Tandem	Three Axle Tandem	Trench	Vibratory Steel
Total Weight, Tons	10	8-12	12-20		5
Compression Rolls, Pounds per Inch Width (Min.)	300	200	240	300	

Pneumatic Tire Rollers

Tire Size Minimum	9.00 x 20
Total Weight Minimum	8 ton

Pneumatic tire rollers shall be self-propelled, reversible units, with vertical oscillation on all wheels on at least one axle. The tires shall be smooth tread and of equal size and diameter. The tires shall be spaced so that the entire gap between adjacent tires will be covered by the smooth tread of the following tire. The steel wheel and pneumatic tire rollers shall be in good mechanical repair and shall be equipped with water sprinkling devices for wetting the rolls. The steel wheel rollers shall be equipped with suitable spring loaded scrapers covering the full width of all rolls.

4.4 Bituminous Distributor. The bituminous pressure distributor should be of an approved type equipped with modern devices for adequate control of pumped application rates. The tank should be well insulated and equipped with suitable heating devices (burners and flues) to assure a uniform, specified, spraying viscosity and temperature. The distributor should be equipped with a fifth wheel tachometer that registers truck speed in feet per minute and a positive displacement pump tachometer that registers in gallons per minute. The spray bar should be of the full circulating type with hydraulic lift and shift capabilities and be equipped with a pressure gauge. The tank should be equipped with suitable pencil or dial thermometers calibrated from 50°F to 300°F (10 to 150°C) and a tank contents gauge with a minimum of 10" (25 mm) diameter dial.

5. Construction

5.1 Subgrade. Adequate drainage shall be provided to prevent undue weakening or damage to the subgrade by moisture or water. The subgrade shall be smoothed, trimmed and compacted to the required line, grade and cross section. During grading, all roots, sod and vegetation shall be removed. The finished subgrade shall be compacted to a density of not less than 90% of the maximum density as determined by AASHO T-180 to a depth of at least 6 in. (150 mm).

The finished subgrade shall have the specified line, grade, cross section and density just prior to placing of the base material. Should the subgrade become rutted or disturbed in any manner, it shall be reshaped and recompacted.

If a sandy subgrade is encountered which is by nature unstable when dry, it shall be kept sufficiently damp to support equipment until covered with base mixture or sub-base. Other types of subgrade shall be firm, showing no signs of damage by equipment until covered by the sub-base or base mixture.

5.2 Sub-Base. Select aggregate of acceptable quality shall be furnished for construction of a sub-base when required under a base course.

To be of acceptable quality the sub-base material shall meet the minimum requirements of the local Highway Department; or one of the three alternates specified below:

Alternates	Test Property	Method of Test	Test Requirements
(1)	California Bearing Ration, % (CBR)	ASTM D1883	20 Min.
(2)	Untreated Resistance R Value	AASHO T190	55 Min.
	Sand Equivalent, %	ASTM D2419	25 Min.
(3)	Plasticity Index	ASTM D424	6 Max.
	Liquid Limit, %	ASTM D423	25 Max.

Aggregates for sub-bases shall be delivered to the subgrade as uniform mixtures and shall be placed in uniform layers. Segregation shall be avoided.

The sub-base material shall be evenly spread, moistened or dried (as required), and compacted to full depth to not less than 95% maximum density as determined by AASHO T-180.

The sub-base shall be smoothed, trimmed and compacted so as to conform to the established line, grade and cross section. The sub-base shall be free from pockets of coarse or fine material. It may be placed in one lift providing the depth of the layer does not exceed 6 inches compacted thickness.

5.3 Prime Cost. A Prime Cost shall be required:

(1) When the asphalt treated base course will be less than 3 in. (75 mm) thick and placed on a loose untreated aggregate subbase,

(2) When the asphalt treated base course will be placed on dry, untreated, lean, or loose, pulverized salvaged base material from the old road,

(3) When the asphalt treated base course will be placed over old deteriorated portland cement concrete slabs, and

(4) When required by the Project Engineer.

5.4 Bituminous Material for Prime. Any suitable grade of bituminous material (such as MC-30 cutback or diluted 1:1 SS-1h or CSS-1h asphalt emulsion) shall be applied, by an approved bituminous distributor, at the rate specified by the Engineer. The prime shall penetrate and cure until the surface is free from pools and resists pickup before proceeding with the pavement construction.

5.5 Bituminous Material for Tack. Existing pavements to be leveled or resurfaced shall receive a light tack coat of suitable bituminous material. The dryness, texture and porosity of the old surface shall be considered for estimating the preferred quantity of tack coat. A popular tack is SS-1h or CSS-1h diluted 1:1 with pure water and applied at the rate of 0.1 to 0.25 gallons (0.5 to 1.2 litres/m^2) of the dilution per square yard; the exact amount depending on the absorptive conditions of the old pavement.

If traffic conditions through the project warrant, the tack coat may be lightly sanded to prevent hazards to traffic during construction.

5.6 Preparation of Aggregate for Mixing (When aggregate is hauled directly to travel plant). When the aggregate to be mixed through the travel plant is a "one-sized" macadam type aggregate with essentially no fraction passing the No. 200 sieve (for example, ASTM Sizes 6, 7 or 8) no preparation may be required if the asphalt selected is the medium setting type. When dense graded aggregate is to be used (containing minus #200 fines) and the asphalt selected for mixing is the medium setting type, the aggregate shall be pre-wetted to the optimum mixing moisture content. The optimum mixing moisture content must be maintained by spraying the stockpiled aggregate several hours before haulage to the dump-fed type travel plant.

5.7 Preparation of Aggregate for Mixing (When aggregate is windrowed for pickup type travel plant). When the aggregate to be mixed through the travel plant is to be windrowed for pickup for the travel plant, the windrowed aggregate shall be maintained at or near optimum mixing moisture content. Water shall be added, as needed, to the windrowed aggregate by sprinkler bar truck, spray-bar distributor or hose and nozzle. The windrowed aggregate shall be maintained uniformly moist by mixing or other means as required.

The volume content of the aggregate windrow per linear foot shall not vary more than (5%) five percent.

Admixtures, if required, shall be thoroughly and uniformly blended into the aggregate windrows. The admixture shall be spread uniformly throughout the aggregate by blade mixing or other methods approved by the Engineer.

5.8 Travel Plant Mixing and Placement. The job should be organized in such a manner that construction traffic over freshly placed mix is avoided whenever possible and is held to an absolute minimum in all cases. Delivery of asphalt and aggregate to the travel plant shall be scheduled to hold shutdowns to an absolute minimum.

The aggregate feeding device (conveyor and adjustable metering gate) should be calibrated at several different settings in the anticipated operating range to determine the quantity fed per minute. The asphalt pump and regulating device shall be calibrated at several different settings in the expected operating range to determine the gallons per minute delivered to the mixing chamber. Throughout construction the aggregate feed rate and the asphalt feed rate shall be controlled and adjusted to maintain the specified gallons of asphalt per ton of aggregate.

The position of the spray-bar nozzles which spray asphalt into the mixing chamber should be positioned far enough forward to achieve uniform coating of the aggregate. It should not be in the extreme forward position if there is any evidence of overmixing. Temperature of the asphalt should be raised (if necessary) to assure easy and uniform pumping and delivery to the mixing chamber. In no case, however, should the temperature exceed 160°F. during heating, the asphalt should be circulated and shall be maintained at a level such that the heating flues are always completely covered.

The transverse spreading devices (augers) should be operated as necessary to maintain an adequate supply of mix in front of the screed. Vertical position of the screed should be adjusted so as to provide the specified mat thickness of mix and/or maintain proper grade. The strike-off screed may ride on skis, runners, or wheels.

Guide string lines should be established by the Engineer parallel to the center line of the roadway for the travel plant to follow in placing initial lanes. Longitudinal pavement edges should closely parallel these established string lines.

Any surface irregularities in the freshly placed mat should be corrected directly behind that travel plant. Excess mix material shall be removed. Low areas or torn spots should be brought to grade and smoothed with rakes or lutes.

When placing travel plant mix adjacent to a lane which already has been laid and rolled, irregularities in the existing edge should be remedied by removing excess mix or placement of additional fresh mix, as necessary. Vertical position of the screed should be controlled carefully to allow for compaction of the loose mix to required density and thickness and to insure a smooth longitudinal joint. Both transverse and longitudinal joints should be staggered in multi lift jobs.

When delays or shutdowns are necessary the aggregate feed and Bitumuls feed should be stopped simultaneously, the pug mill should continue to operate until all of the mixture has been discharged, the travel plant machine shall move forward until all of the mixture has been spread, and the potential transverse joint should be squared and leveled. The screed shall be cleaned as often as necessary to prevent streaking or tearing of the fresh loose mat.

5.9 Compacting the Mixture. Compaction of the treated base material shall commence immediately after it has been spread on the subgrade or at the direction of the Engineer. Each lift of the mixture shall be compacted to at least 95% of the laboratory density.

Rolling shall commence at the outer edges of the base course and progress toward the center.

Breakdown and intermediate rolling may be by pneumatic tire, vibratory steel wheel, three wheel steel wheel or tandem steel wheel roller as best suits the particular grading, type, and richness of the mixture. Finish rolling shall be by tandem steel wheel, three axle tandem steel wheel or self-propelled vibratory steel wheel roller. Rolling shall continue until all ruts, roller marks, and tire prints of the initial breakdown rolling are smoothed to a true cross section.

The steel wheels should be kept wet during rolling and spring loaded scraper blades shall be maintained in proper adjustment to keep the wheels clean. Sudden stops and starts and sharp turns should be avoided. Rollers should not be left standing upon the fresh mixture. Small quantities of detergent in the roller wetting water may be beneficial for preventing pickup on the rolls.

5.10 Dry Choke. If a layer of travel plant mixture is subjected to traffic prior to placement of a succeeding course, it should receive a uniform application of 5 to 10 pounds per square yard (2.7 to 5.4 kg/m^2) dry choke aggregate (coarse sand or fine chips) to avoid pickup. The dry choke should be spread just after the initial rolling.

5.11 Secondary Rolling. After the mixture has developed sufficient mat cohesion to avoid undue displacement under the roller it may be rolled again following the normal rolling procedures.

5.12 Tolerance. No portion of the completed base should vary more than 1/4 in. (6 mm) from a 10-foot (3 m) straightedge placed in any direction where the planned grade or cross-section is in one plane, or from a 10-foot (3 m) template laid transversely and conforming with the specified crown.

5.13 Black Seal. If it is necessary to open the new base course or leveling course to temporary traffic before the succeeding layer (or surface course) is constructed, the cured base course may be sealed by applying 0.15 to 0.25 gallons per square yard (.7 to 1.2 litres/m^2) of one to one (1:1) diluted asphalt emulsion grades SS-1h or CSS-1h. The application shall be allowed to cure until no pickup occurs before traffic is permitted on the base course.

(Caution: To avoid pickup and whipoff the base mixture should be cured throughout its depth before the seal is applied.)

6. Method of Measurement

6.1 The amount of select aggregate furnished and placed as subbase material under section 5.2 shall be measured in cubic yards (m^2), compacted, in place, on the grade.

6.2 The "Bituminous Material for Primes furnished, applied and accepted as prime coat under section 5.3 shall be measured in U.S. gallons (litres) at 60°F (15°C), or in tons.

6.3 The "Bituminous Material for Tack" furnished, applied and accepted as Tack Coat under section 5.5 shall be measured in undiluted U.S. gallons (litres) at 60°F (15°C), or in tons.

6.4 The "Bituminous Emulsified Asphalt for Travel Plant Mixing" furnished and mixed through the travel plant for the base course mixture shall be measured in U.S. gallons (litres) at 60°F (15°C), or in tons.

6.5 The aggregate hauled to the jobsite, dumped into the receiving hopper of the travel plant or placed in sized windrows, as the case may be, shall be measured in tons to the nearest tenth of a ton, no deduction being made for moisture. Truckload net weights may be tallied for this measurement.

Note: If it is intended that in-place aggregate is to be scarified and shaped into windrows for subsequent mixing in-place see Construction Specification B-5-C. This specification (B-5-B) covers only the methods of construction where the aggregate is furnished, hauled, and dumped into the travel plant or is windrowed on the subbase or subgrade for pickup by the travel plant.

6.6 The diluted asphalt emulsion furnished and applied and used and accepted as seal on the cured base course shall be measured in undiluted U.S. gallons at 60°F (15°C) or undiluted tons (kg) to the nearest one hundredth ton (kg).

The volume measured or weighed and reported shall be the undiluted emulsion.

6.7 Water Used for Prewetting Aggregate. The water used for prewetting the stockpiled aggregate or the windrowed aggregate as directed will be measured in thousands of U.S. gallons (litres) either volumetrically or by weight.

6.8 Admixture (When Required). Admixture such as hydraulic cement, hydrated lime, soil or clay, etc., if required to be blended into the aggregate either at the stockpile loading operations or in the windrows on the grade will be measured in tons to the nearest hundredth of a ton. It will be necessary to define the exact admixture material and the exact percentages to be blended if this item is required.

6.9 Chips for Dry Choke. The crushed aggregate (such as ASTM Size No. 8 or No. 9 or dry coarse sand) furnished, hauled, spread, accepted and used as dry choke will be measured in tons to the nearest tenth of a ton.

7. Basis of Payment

7.1 The cubic yardage of select aggregate furnished, accepted and placed for subbase material, shall be paid for at the contract unit price per cubic yard bid for "Select Aggregate for Sub-Base Material".

7.2 The "Bituminous Material for Prime" used for prime coat furnished, accepted and used on the project shall be paid for at the contract unit price per gallon (litre) or per ton bid for "Bituminous Material for Prime".

7.3 The "Bituminous Material for Tack" used for Tack Coat furnished, applied and accepted shall be paid for at the contract unit per gallon (litre) or per ton bid for "Bituminous Material for Tack."

7.4 The "Emulsified Asphalt for Travel Plant Mixing" furnished and mixed through the travel plant for Bitumuls treated base course mixture shall be paid for at the contract unit price per gallon (litre) or per ton bid for "Bitumuls Emulsified Asphalt for Travel Plant Mixing" and as measured under section 6.4.

7.5 For the aggregate used for the asphalt treated base mixture through the travel plant, the contractor will be paid the contract unit price per ton bid for "Aggregate for Travel Plant Mixing." This pay item will be measured in tons as specified in section 6.5 and payment will constitute full compensation for furnishing, hauling, mixing, spreading, aerating if required, and compacting the base mixture, as well as all tools, signs, barricades, flagman, traffic control, and equipment not otherwise included in pay items necessary to complete the work in a workmanlike manner according to the plans and as directed by the Engineer.

7.6 The emulsion used for seal on the cured base course will be paid for at the contract unit price per undiluted gallon (litre), or per undiluted ton bid for "Emulsified Asphalt for seal".

Payment will be full compensation for diluting the emulsion, for suitable water for dilution, for heating, and application of the seal.

7.7 The water used for prewetting aggregate will be paid for at the contract unit price per thousand gallons (litre) bid for "Water for Prewetting Aggregate".

7.8 Any admixture used and accepted on the project will be paid for at the contract unit price per ton bid for "Admixture".

7.9 The chips for dry choke as measured under article 6.9 shall be paid for at the contract unit price bid for "Chips for Dry Choke".

8. Seasonal and Temperature Limitations

8.1 There should be no travel plant mixing operations when the ambient air temperature is below 50°F (10°C), nor when rain is imminent, or when other conditions are obviously unsuitable.

8.2 There should be no prime or tack coating operations when the surface temperature of the pavement is below 50°F (10°C), nor when rain is imminent.

9. Limitation of Warranty and Liability

Disclaimer of Warranties. This specification reflects successful performance experience, and is intended to provide a guide to approved construction practices and materials. However, as workmanship, weather conditions, construction equipment, quality of other materials and other variable factors affecting results are all beyond our control, there is NO WARRANTY OF FITNESS OR MERCHANTABILITY, EXPRESS OR IMPLIED, THAT FOLLOWING THIS SPECIFICATION OR USING THE MATERIALS COVERED THEREBY WILL ASSURE SATISFACTORY RESULTS IN ALL CASES.

APPENDIX C

COST DATA AND ECONOMIC ANALYSIS

INTRODUCTION

This appendix contains information defining costs associated with pavement construction, reconstruction, and maintenance operations. In addition, a simplified economic analysis method is described which will allow the engineer responsible for the construction, rehabilitation, and maintenance of roadway network to allocate his monetary resources in an optimum manner.

COST DATA

Data are included in this appendix which define costs associated with pavement construction, reconstruction, and maintenance operations. These costs are intended to be representative only. If costs for these operations are available from local agencies' historical records, they should be substituted appropriately.

Construction Costs

Costs of common pavement construction operations are shown in Table 20. These costs are considered representative of average in-place costs in the United States. Costs are based on pavement layers in the range of 4 to 8 inches (102 to 203 mm) for untreated base and stabilized layers. Asphalt concrete costs are typical of 1.5 to 3 inch (38 to 97 mm) lifts while portland cement concrete costs are typical for pavements 8 to 10 inches (203 to 254 mm) in thickness.

Rehabilitation Costs

Costs associated with selected rehabilitation operations are shown on Table 21. The common rehabilitation activities of seal coats and asphalt concrete can be found on Table 20. Costs associated with recycling operations can be found in reference 69.

Maintenance Costs

Costs associated with flexible pavement maintenance operations are shown on Table 22 and with rigid pavement maintenance operations on Table 23. Costs were obtained from the states of Arizona, California, Nevada, and North Dakota and are representative of costs in 1976.

A general description for each maintenance activity has been prepared and is shown on the tables together with the average, low,

Table 20. Cost of Common Pavement Construction Operations - 1978 (69)

CONSTRUCTION OPERATION	REPRESENTATIVE COSTS $ PER SQ. YARD - IN.	
	AVERAGE	RANGE
Crushed stone base	0.50	0.30 - 0.60
Gravel base	0.40	0.20 - 0.60
Lime stabilized subgrade	0.25	0.15 - 0.35
Cement stabilized subgrade	0.30	0.20 - 0.40
Cement treated base	0.80	0.60 - 1.10
Asphalt treated base	0.80	0.60 - 1.00
Lime--fly ash--aggregate base	0.70	0.60 - 0.80
Chip seal	0.35	0.20 - 0.45
Asphalt concrete	1.00	0.70 - 1.20
Portland cement concrete	1.40	1.00 - 2.00

1 $yd^2 = 8.361 \times 10^{-1} m^2$

1 in. $= 2.54 \times 10^{-2}$ m

Table 21. Costs of Common Recycling Operations - 1978 (69)

RECYCLING OPERATION	REPRESENTATIVE COSTS $ PER SQ. YARD - IN.*	
	AVERAGE	RANGE
Heat and Plane Pavement - 3/4 inch depth	0.25	0.15 - 0.50
Heat and Scarify Pavement - 3/4 inch depth	0.40	0.15 - 0.70
Cold Mill Pavement	0.60	0.30 - 1.00
Rip, Pulverize and Compact - Existing Pavement less than 2 inches of Asphalt Concrete	0.20	0.13 - 0.35
Rip, Pulverize, Stabilize and Compact - Existing Pavement less than 2 inches of Asphalt Concrete	0.35	0.20 - 0.40
Rip, Pulverize and Compact - Existing Pavement greater than 2 inches of Asphalt Concrete	0.25	0.15 - 0.40
Rip, Pulverize, Stabilize and Compact - Existing Pavment Greater than 2 inches of Asphalt Concrete	0.40	0.25 - 0.50
Remove and Crush Portland Cement Concrete	0.50	0.30 - 0.70
Remove and Crush Asphalt Concrete	0.30	0.20 - 0.50
Cold Process - Remove, Crush, Place, Compact, Traffic Control - (Cold Process) without Stabilizer	0.40	0.30 - 0.60
Cold Process - Remove, Crush, Mix, Place, Compact, Traffic Control - (Cold Process) with Stabilizer	0.50	0.35 - 0.70
Hot Process - Remove, Crush, Place, Compact, Traffic Control - without Stabilizer	0.60	0.45 - 0.90
Hot Process - Remove, Crush, Mix, Place, Compact, Traffic Control - with Stabilizer	0.70	0.50 - 1.00

*Costs are for a square yard inch except where listed.

1 yd = 8.361×10^{-1} m^2

1 in. = 2.54×10^{-2} m

Table 22. Unit Cost for Flexible Pavement Maintenance Operations

DESCRIPTIVE TITLE	GENERAL DESCRIPTION	STATE	NO.	REPORTED AV. UNIT COST, DOLLARS	SUGGESTED COST, DOLLARS			
					AVG.	LOW	HIGH	UNIT MEAS.
Fog Seal - Partial Width	Light application of diluted emulsion or a proprietary material over a partial lane.	ARI	109	0.095/yd^2	.095	.075	.131	yd^2
Fog Seal - Full Width	Light application of diluted emulsion or a proprietary material over a full lane width in a continuous section.	ARI CAL NEV ND	108 01.983 101.06 435	0.069/yd^2 0.06/yd^2 0.06/yd^2 0.11/yd^2	.06	.05	.11	yd^2
Chip Seal - Partial Width	Application of asphalt and cover aggregate to a limited area.	ARI CAL NEV ND	104 01-051 101.05 412	0.36/yd^2 0.41/yd^2 0.23/yd^2 0.26/yd^2	.35	.23	.41	yd^2
Chip Seal - Full Width	Application of asphalt and cover aggregate to a full lane width in a continuous section.	ARI CAL NEV ND	106 01-054 101.09 422	0.18/yd^2 0.24/yd^2 0.23/yd^2 0.21/yd^2	.21	.18	.24	yd^2
Surface Patch-Hand Method	Application of a Permix material to the surface of the pavement by hand method.	ARI CAL NEV	102 01-031 101.02	34.56/yd^3 147.00/yd^3 123.60/yd^3	130.00	60.00	170.00	yd^3
Surface Patch-Machine Method	Application of a Premix material to the surface of the pavement with machine.	ARI CAL CAL CAL CAL NEV ND	102 01-021 01-022 01-023 01-024 101.03 421	34.56/yd^3 52.50/yd^3 43.00/yd^3 28.50/yd^3 40.40/yd^3 27.96/yd^3 22.35/yd^3	28.00	20.00	40.00	yd^3
Digout & Repair Hand Method	Removal & repair of limited areas by use of hand tools.	ARI CAL ND	101 01-034 411	112.39/yd^3 145.00/yd^3 55.34/yd^3	110.00	40.00	160.00	yd^3
Digout & Repair Machine Method	Removal & repair of limited areas by use of mechanized equipment.	ARI CAL NEV	105 01-011 101.01	27.38/yd^3 68.00/yd^3 17.35/yd^3	25.00	10.00	70.00	yd^3
Crack Pouring	Pouring cracks in flexible pavement with asphalt material (may include cleaning with compressed air & covering with sand.	ARI CAL CAL NEV ND	103 01-041 01-042 101.07 414	3.38/gal 4.83/gal 6.41/gal 3.00/gal 1.18/gal	3.25	1.10	6.50	gal
Asphalt Concrete Overlay	Application of an asphalt concrete overlay usually less than about 2 inches.	TEX US		21.00*/ton 15.12*/ton	31.00	23.00	43.00	yd^3

*Cost per ton   Metric Conversions: 1 yd^2 = 0.83 m   1 yd^3 = 0.76 m   1 ton = 907 kg

Table 23. Unit Cost for Rigid Pavement Maintenance Operations (1977) (69)

DESCRIPTIVE TITLE	MAINTENANCE ACTIVITY			REPORTED AV. UNIT COSTS, DOLLARS	SUGGESTED UNIT COST, DOLLARS			
	GENERAL DESCRIPTION	STATE	NO.		AVG.	LOW	HIGH	UNIT OF MEASURE
Mudjacking	Drilling holes and pumping concrete slurry under slab to fill the voids and raise the slab to grade.	CAL	02-011	7.28/yd^2	7.25			sq yd
Temporary Patching	Patch with bituminous material.	CAL NEV	02-021	25.50/yd^3 106.26/yd^3	80	20	160	cu yd
Permanent Patching	Patch with P.C.C.	NEV	111.02	371.25/yd^3	375			cu yd
Joint Sealing	Cleaning joint, pour joint and apply sand as required.	CAL CAL NEV	02-042 02-043 111.05	5.75/gal 4.77/gal 10.00/gal	7.00	5.00	12.00	gal
Expansion Joint Repair	Cut along distressed area. Clean out area, place filler material.	NEV	111.06	6.79/lin ft	6.75	5.00	40.00	lin ft

Metric Conversion:

1 yd^2 = 0.83 m^2

1 yd^3 = 0.76 m^3

1 gal = 0.26 litre

1 ft = 0.305 m

and high unit costs for these activities. The reported suggested costs are the author's best estimate of representative unit costs for the stated maintenance activity. The wide range of reported unit costs for this condensed list of activities is due in part to:

1. Different crew sizes utilized in the various states
2. Different equipment requirements for various states
3. Differences in maintenance work activity as defined by various states
4. Variety of traffic conditions under which maintenance is performed
5. Type of facility on which maintenance activities are performed
6. Amount of work performed per lane mile

Maintenance unit cost information has been converted to costs per square yard (square m) of total pavement surface area treated and cost per lane mile (km) (Table 24). In order to develope these costs, assumptions were made as to the thickness and extent of the area treated. Costs associated with maintenance activities of different thicknesses and extent can be calculated from Tables 22 and 23 or by consulting reference 69.

The summary of information contained on the previous tables is for 10 flexible and 5 rigid pavement maintenance activities. As stated, these costs are based on the data obtained from four states. If the reader has need of determining maintenance costs for activities other than those listed on the tables, it will be necessary to obtain data from a local state, county, or city performing that activity.

The reader is reminded that the maintenance activities described in this report are normally performed on pavements with certain specific types of distress. For example, fog seals and chip seals are popular maintenance or rehabilitation activities that are used to correct raveling flexible pavements. Typical types of flexible pavement distress and maintenance activities associated with maintenance of these types of distress are shown in Table 25. The reader is referred to reference 70 for a detailed description of the distress types.

Table 24. Representative Costs for Maintenance and Rehabilitation Activities - 1977 (69)

MAINTENANCE ACTIVITY	COST DOLLARS* PER SQ. YD.	COST DOLLARS* PER LANE MILES	PERCENT OF TOTAL PAVEMENT AREA TREATED
Fog Seal - Partial Width	0.045	320	50 percent
Fog Seal - Full Width	0.06	420	100 percent
Chip Seal - Partial Width	0.06	420	15 percent
Chip Seal - Full Width	0.21	1,500	100 percent
Surface Patch - Hand Method	0.10	700	2.5 percent 1 inch thick
Surface Patch - Machine Method	0.08	560	10 percent 1 inch thick
Digout & Repair - Hand Method	0.25	1,760	2 percent 4 inches thick
Digout & Repair - Machine Method	0.20	1,400	5 percent 6 inches thick
Crack Pouring	0.12	850	250 lin. ft. per station
Asphalt Concrete Overlay	1.90	13,400	100 percent 2 inches thick

*Costs are for square yards of total pavement surface maintained. For example, surface patching by the hand method may have been applied over only 5 percent of total pavement surface area, yet costs reported are for the total pavement area maintained or one mile of pavement.

Metric Conversions:

1 yd^2 = 0.83 m^2
1 mi = 1609 m
1 in. = 0.024 m
1 ft. = 0.305 m

Table 25. Maintenance Activities Associated with Flexible Pavement Distresses

TYPE OF DISTRESS	MAINTENANCE ACTIVITY	
Rutting	Surface Patch - Hand Surface Patch - Machine	Asphalt Concrete Overlay
Raveling	Fog Seal - Partial Width Fog Seal - Full Wdith	Chip Seal - Partial Width Chip Seal - Full Width
Flushing (Bleeding)	Overlay Chip Seal - Full Width	
Corrugations	Surface Patch - Hand Surface Patch - Machine Asphalt Cone - Overlay	Digout & Repair - Hand Digout & Repair - Machine
Alligator Cracking	All maintenance operations could be used.	
Longitudinal Cracking	Fog Seal - Partial Width Fog Seal - Full Width Crack Pouring	Chip Seal - Partial Chip Seal - Full Width Asphalt Cone - Overlay
Transverse Cracking	Crack Pouring Chip Seal - Full Width	Asphalt Concrete Overlay
Patching	Surface Patch - Hand Surface Patch - Machine Chip Seal - Full Width	Digout & Repair - Hand Digout & Repair - Machine Asphalt Concrete Overlay
Failures	Surface Patch - Hand Surface Patch - Machine Asphalt Cone Overlay	Digout & Repair - Hand Digout & Repair - Machine

ECONOMIC ANALYSIS

The engineer responsible for the construction rehabilitation and maintenance of a road network is responsible for allocating his monetary resources in an optimum manner. Thus we must decide on what portion of the roadway network he intends to construct, rehabilitate, and maintain as well as what specific rehabilitation and/or maintenance action is most appropriate for a particular roadway segment. Project feasibility is determined at the network level by comparing the needs of the entire roadway system. Selection of a specific rehabilitation or maintenance alternative for a given project requires that a variety of alternatives be considered from an economic standpoint. The economic tools used by the engineer to make those "network" and "project" decisions are nearly the same, with the amount of detailed information required as the major difference.

This appendix considers only the technique suitable for selection of a construction rehabilitation and/or maintenance strategy for a particular project. The techniques available make use of the principles of engineering economy and methods of economic evaluation. Thus cost information is required together with information concerning the life of various rehabilitation alternatives. Cost information must be projected for the life of the project, and techniques utilized to reduce these costs at various ages after reconstruction to some "common denominator". Hence, the term "life cycle analysis" is often utilized. These "common denominator" costs can be compared and the least cost solution selected.

Costs Associated with Pavement Rehabilitation

The initial and recurring costs that an agency may consider in the economic evaluation of alternative construction and rehabilitation strategies have been defined in reference 71 and include the following:

1. Agency costs
    a. Initial capital costs of construction or rehabilitation,
    b. Future capital costs of reconstruction or rehabilitation (overlays, seal coats, etc.),
    c. Maintenance costs, recurring throughout the design period,
    d. Salvage return or residual value at the end of the design period,
    e. Engineering and administration and
    f. Costs of investments.

2. User costs:
    a. Travel time,
    b. Vehicle operation,
    c. Accidents,
    d. Discomfort, and
    e. Time delay and extra vehicle operating costs during resurfacing or major maintenance.
3. Nonuser costs

Certainly all of these costs should be included if a detailed economic analysis is desired. However, definition of many of these costs is difficult while other costs do not significantly affect the analysis of alternatives for a given roadway segment. For the sake of simplicity, the method of analysis suggested for use will consider only the following costs:

1. Initial capital costs of construction and/or rehabilitation,
2. Future capital costs of reconstruction or rehabilitation, and
3. Maintenance costs.

It is suggested, however, that certain user costs such as time delay costs during rehabilitation be considered on high traffic volume facilities. The reader is directed to references 26 and 71 for additional detail.

Selection of Discount Rate (Interest Rate)

The discount rate (interest rate) (rate of return) is utilized to reduce future expected costs for projects to present-day terms for economic comparison purposes. The value selected for discount rate deserves careful attention by the engineer. The rate selected is normally between 4 to 10 percent while the actual value selected should be based upon consideration of the following:

1. Interest rate currently charged to borrow capital,
2. Rate of return expected of private investments,
3. Rate of return expected on public works investments, and
4. Risks and uncertainties associated with investments.

It should be noted that construction and rehabilitation alternatives with large initial costs and low maintenance or user costs are favored by low interest rates. Conversely, high interest rates favor strategies that combine low initial costs with high maintenance and user costs.

A discount rate of 8 percent has been utilized together with a 20-year analysis period for the example presented in this Appendix. Present worth factors and capital recovery factors for discount rates of 6, 7, and 8 percent are shown in Table 26. Values for other discount rates can be found in reference 26 or textbooks on engineering economy. Both present worth and the uniform annual cost method are illustrated below. Costs are estimated in terms of dollars per square yard; however, costs in terms of dollars per lane-mile is also a convenient unit.

Example Problem*

A nine-mile pavement section is to be constructed in central Texas. Two pavement sections have been suggested for use on this roadway. Plan 1 consists of construction of a pavement containing 6 inches of lime stabilized subgrade, 8 inches of crushed stone base, and 2 inches of asphalt concrete surfacing. Overlays are scheduled on a 7-year cycle (Table 27). Plan 2 consists of constructing a pavement containing 6 inches of lime stabilized subfrade, 8 inches of asphalt treated base, and 2 inches of asphalt concrete. Overlays will not be required during the 20-year life cycle (Table 28).

The following cost estimates were utilized for the initial construction:

1. Lime stabilization - \$0.25 per yd^2-in.
2. Asphalt stabilization - \$0.80 per yd^2-in.
3. Crushed stone base - \$0.50 per yd^2-in.
4. Asphalt concrete - \$1.00 per yd^2-in.

Initial construction costs for Plan 1 are therefore \$7.50 per yd^2, and \$9.90 per yd^2 for Plan 2. Routine maintenance costs were forecast based on experience of the local highway department district and costs shown on Tables 22 and 24.

From both a present worth and uniform annual cost basis with an 8 percent rate of return, Plan 1 is favored (\$9.72 versus \$10.16 and

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*Only English units will be used in the example problem for the sake of clarity.

Table 26. Present Worth and Capital Recovery Factors

	PRESENT WORTH FACTOR			CAPITAL RECOVERY FACTOR		
	INTEREST RATE			INTEREST RATE		
YEARS	6	7	8	6	7	8
1	0.9434	0.9346	0.9259	1.06000	1.07000	1.08000
2	0.8900	0.8734	0.8573	0.54544	0.55309	0.56077
3	0.8396	0.8163	0.7938	0.37411	0.38105	0.38803
4	0.7921	0.7629	0.7350	0.28859	0.29523	0.30192
5	0.7473	0.7130	0.6806	0.23740	0.24389	0.25046
6	0.7050	0.6663	0.6302	0.20336	0.20980	0.21632
7	0.6651	0.6227	0.5835	0.17914	0.18555	0.19207
8	0.6274	0.5820	0.5403	0.16104	0.16747	0.17401
9	0.5919	0.5439	0.5002	0.14702	0.15349	0.16008
10	0.5584	0.5083	0.4637	0.13587	0.14238	0.14903
11	0.5268	0.4751	0.4289	0.12679	0.13336	0.14008
12	0.4970	0.4440	0.3971	0.11928	0.12590	0.13270
13	0.4688	0.4150	0.3677	0.11296	0.11965	0.12652
14	0.4423	0.3878	0.3405	0.10758	0.11434	0.12130
15	0.4173	0.3624	0.3152	0.10296	0.10979	0.11683
16	0.3936	0.3387	0.2919	0.09895	0.10586	0.11298
17	0.3714	0.3166	0.2703	0.09544	0.10243	0.10963
18	0.3505	0.2959	0.2502	0.09236	0.09941	0.10670
19	0.3305	0.2765	0.2317	0.08962	0.09675	0.10413
20	0.3118	0.2584	0.2145	0.08718	0.09439	0.10185
21	0.2942	0.2415	0.1987	0.08500	0.09229	0.09983
22	0.2775	0.2257	0.1839	0.08305	0.09041	0.09803
23	0.2618	0.2109	0.1703	0.08128	0.08871	0.09642
24	0.2470	0.1971	0.1577	0.07968	0.08719	0.09498
25	0.2330	0.1842	0.1460	0.07823	0.08581	0.09368
26	0.2198	0.1722	0.1352	0.07690	0.08456	0.09251
27	0.2074	0.1609	0.1252	0.07570	0.08343	0.09145
28	0.1956	0.1504	0.1159	0.01459	0.08239	0.09049
29	0.1846	0.1406	0.1073	0.07358	0.08145	0.08962
30	0.1741	0.1314	0.0994	0.07265	0.08059	0.08883

Table 27. Economic Analysis of Plan 1

YEAR	COST, DOLLARS PER SQUARE YARD	PRESENT WORTH FACTOR, 8%	PRESENT WORTH DOLLARS
INITIAL COST	7.50 initial construction	1.000	7.50
1		0.9259	
2		0.8573	
3	0.07 routine maintenance	0.7938	0.056
4	0.10 routine maintenance	0.7350	0.074
5	0.12 routine maintenance	0.6806	0.082
6	0.12 routine maintenance	0.6302	0.076
7	1.80 2-inch overlay	0.5835	1.050
8		0.5403	
9		0.5002	
10	0.07 routine maintenance	0.4632	0.032
11	0.10 routine maintenance	0.4289	0.043
12	0.12 routine maintenance	0.3971	0.048
13	0.12 routine maintenance	0.3677	0.044
14	1.80 2-inch overlay	0.3405	0.613
15		0.3152	
16		0.2919	
17	0.07 routine maintenance	0.2703	0.019
18	0.10 routine maintenance	0.2502	0.025
19	0.12 routine maintenance	0.2317	0.028
20	0.12 routine maintenance	0.2145	0.026

TOTAL = 12.33 TOTAL = 9.716 ←

UNIFORM ANNUAL COST = PRESENT WORTH x CAPITAL RECOVERY FACTOR

= 9.716 x 0.10185

= 0.990 ←

Table 28. Economic Analysis of Plan 2

YEAR	COST, DOLLARS PER SQUARE YARD	PRESENT WORTH FACTOR, 8%	PRESENT WORTH DOLLARS
INITIAL COST	9.90 initial construction	1.0000	9.90
1		0.9259	
2		0.8573	
3		0.7938	
4		0.7350	
5		0.6806	
6		0.6302	
7		0.5835	
8	0.07 routine maintenance	0.5403	0.038
9		0.5002	
10	0.10 routine maintenance	0.4632	0.046
11		0.4289	
12	0.12 routine maintenance	013971	0.048
13		0.3677	
14	0.12 routine maintenance	0.3405	0.041
15		0.3152	
16	0.12 routine maintenance	0.2919	0.035
17		0.2703	
18	0.12 routine maintenance	0.2502	0.030
19		0.2317	
20	0.12 routine maintenance	0.2145	0.026

TOTAL = 10.67

TOTAL = 10.164 ←

UNIFORM ANNUAL COST = PRESENT WORTH x CAPITAL RECOVERY FACTOR

= 10.160 x 0.10185

= 1.035 ←

$0.99 versus $1.04). It should be realized that several assumptions including pavement life, maintenance costs, rehabilitation costs, and discount rates were made. For example, if a lower discount rate were utilized, Plan 2 would be favored over Plan 1. Present worth for 0 percent discount rates are shown on Tables 27 and 28. Plan 1 is $12.33 and Plan 2 is $10.67 for 0 percent discount rates. Selection of Plan 1 over Plan 2 should be made based on more detailed estimates of life and cost figures. The sensitivity of the analyses to these estimates should be investigated.

Table 29 is a sample calculation sheet for a rehabilitation alternative. The present worth and capital recovery factor are those for 8 percent discount rate. Other values can be substituted when required.

Table 29. Calculation Form for Economic Analysis

	COST, DOLLARS PER SQUARE YARD	PRESENT WORTH FACTOR, 8%	PRESENT WORTH, DOLLARS
INITIAL COST		1.0000	
1		0.9259	
2		0.8573	
3		0.7938	
4		0.7350	
5		0.6806	
6		0.6302	
7		0.5835	
8		0.5403	
9		0.5002	
10		0.4632	
11		0.4289	
12		0.3971	
13		0.3677	
14		0.3405	
15		0.3152	
16		0.2919	
17		0.2703	
18		0.2502	
19		0.2317	
20		0.2145	

TOTAL = ________ TOTAL = ________ ←

UNIFORM ANNUAL COST = PRESENT WORTH x CAPITAL RECOVERY FACTOR

= ____________ x 0.10185

= ________ ←

APPENDIX D

ENERGY ASSOCIATED WITH CONSTRUCTION, REHABILITATION, AND MAINTENANCE OPERATIONS

INTRODUCTION

This appendix contains information defining energy associated with highway construction, rehabilitation, and maintenance operations. These energy requirements are intended to be representations only. If energy requirements for these operations are available from the agencies' historical records, they should be substituted appropriately.

The preferred approach for calculation of the energy requirements is to use a step-by-step procedure for each phase of the construction, rehabilitation, or maintenance operation utilizing the energy data summarized below. Since this is a time consuming process, summary data is also presented for several operations.

ENERGY EQUIVALENTS

A wide variety of equipment and processes are utilized to produce, transport, and place materials associated with highway construction, rehabilitation, and maintenance activities. Typical equivalencies for a wide variety of fuels associated with these operations are shown in Table 30. It should be noted that as the density of the petroleum product increases, the energy equivalent increases. Asphalt cement, which has a high density, has a relatively large energy equivalent. It also should be noted that asphalt has not been considered as a fuel source but rather as a construction material in this report. Thus if asphalt cement, cutback asphalt, or emulsified asphalt are materials utilized as a part of the maintenance or rehabilitation activity, their energy equivalencies as a fuel are not considered (2). The potential is there, however.

To aid the reader in conversion from one energy unit to another energy unit, the following is offered:

1 KWh = 3412 Btu
1 hp-hr = 2547 Btu
1 hp = 0.7457 kW
1 kWh = 1.341 hp
1 Btu = 1055 J
1 J = 0.000948 Btu

Table 30. Fuel Equivalents

FUEL	ENERGY EQUIVALENT
Gasoline	125,000 BTU/gal (2)
Kerosene	135,000 BTU/gal (2)
Fuel Oil, No. 1 (API 42)	135,000 BTU/gal (2)
Fuel Oil, No. 2 (API 35) (diesel)	139,000 BTU/gal (2)
Fuel Oil, No. 3 (API 28)	143,000 BTU/gal (2)
Fuel Oil, No. 4 (API 20)	148,500 BTU/gal (2)
Fuel Oil, No. 5 (API 14)	152,000 BTU/gal (2)
Fuel Oil, No. 6 (API 10)(Bunker C)	154,500 BTU/gal (2)
Natural Gas	1,000 BTU/ft (2)
Propane Gas	91,000 BTU/gal (2)
Butane Gas	100,000 BTU/gal (2)
Asphalt Cement	158,000 BTU/gal (72) 19, 045 BTU/lb
Coal	11,670 BTU/lb (73)
Petroleum Coke	14,470 BTU/lb (73)
Lignite	6000 to 9000 BTU/lb

Metric Conversion:

1 BTU/gal = 278.7 J/l

1 BTU/ft^3 = 37.26 J/l

1 BTU/lb = 2324 J/kg

A British thermal unit (Btu) is the quantity of heat required to raise the temperature of one pound of water one degree Fahrenheit when water is at or near 39.2°F (4°C). A Joule is a unit of work and energy in the SI System. 4.186 Joules are required to riase one gram of water 1°C.

Equipment

Energy requirements for various types of vehicles and equipment associated with construction, rehabilitation, and maintenance are shown on Table 31 and Table 32. Table 31 gives energy requirements for automobiles and trucks while Table 32 includes various maintenance equipment. Appropriate references are included. Truck energy requirements are based on a loaded truck one way with a return empty trip. Thus, the total round-trip mileage should be multiplied by the values in the table to get the energy required for hauling.

Production and Manufacture

Energy requirements for the manufacture of asphalt products, portland cement, steel, and lime are shown on Table 33. Energy associated with operations involving the production of aggregates, asphalt concrete, and portland cement concrete are shown in Tables 34, 35, and 36, respectively. In some cases different values have been reported by various agencies. These differing values are given in the table.

Maintenance and Rehabilitation Activities

Energy requirements associated with the performance of routine maintenance and rehabilitation activities are shown in Table 37. The specific activities for which energy data have been calculated are:

1. Fog Seal - Partial Width
2. Fog Seal - Full Width
3. Chip Seal - Partial Width
4. Chip Seal - Full Width
5. Surface Patch - Hand Method
6. Surface Patch - Machine Method
7. Digout and Repair - Hand Method
8. Digout and Repair - Machine Method
9. Crack Pouring

Table 31. Energy Requirements for Automobile and Truck Operation

TYPE OF VEHICLE	ENERGY REQUIREMENTS BTU/mi	BTU/hr	BTU/ton mi	REF.
Automobile	7,230			
Stationwagon	7,760			
Pickup	11,400			
Maintenance Trucks--Diesel	26,700	97,300		
Maintenance Trucks--Gasoline	26,600	100,000		
Maintenance Trucks--1 ton	15,600			
Maintenance Truck--2 Axle	27,500			
Distributor Truck--Gasoline	31,300			
Truck Tractor--Diesel	30,400			
Truck--2 Axle, 6 Tire, Gasoline			11,000	2
Truck--3 Axle, Gasoline			4,270	2
Truck--3 Axle, Diesel			3,800	2
Truck--3 Axle (combination) Gasoline			7,440	2
Truck--3 Axle (combination) Diesel			5,840	2
Truck--4 Axle (combination) Gasoline			5,040	2
Truck--4 Axle (combination) Diesel			3,270	2
Truck--5 Axle (combination) Gasoline			2,900	2
Truck--5 Axle (combination) Diesel			1,960	2

Metric Conversion:

1 BTU/mi = 656.1 J/km
1 BTU/hr = 1055 J/hr
1 BTU/ton mi = 0.723 J/kg km

Table 32. Energy Requirements for Miscellaneous Maintenance and Rehabilitation Equipment

TYPE OF VEHICLES	ENERGY REQUIREMENT		REF
	BTU/mi	BTU/hr	
Front End Loader--2 cu yd, Diesel		6,950	
Front End Loader--1.5 cu yd, Gasoline		5,000	
Loader for Aggregates		875,000	2
Front End Loader, Diesel		222,000	2
Motor Grader--23,000 lb., Diesel		6,950	
Grader, Diesel		375,000	
Rollers		625,000	2
Roller		111,000	
Striping Machine, Self Contained		125,000	
Hand Striping Machine		62,500	
Mower, Roadside		125,000	
Mower, Landscape		46,800	
Tractor, Farm Type		375,000	
Spreader, Self Propelled		338,000	
Broom, Mechanical		125,000	
Dozer, Track Type		417,000	
Crushing/Screening Plant		695,000	
Asphalt Paver		626,000	2

Metric Conversion:

1 BTU/mi = 656.1 J/km
1 BTU/hr = 1055 J/hr

Table 33. Energy Associated with Manufacturing

ITEM	ENERGY REQUIREMENTS			REF.
	BTU/GAL	BTU/LB	BTU/TON	
Asphalt Cement	2,500	300	600,000	2
Emulsified Asphalt	2,000	240	480,000*	2
Cutback Asphalt	2,500	300	600,000**	2
Portland Cement		3,150	6,300,000	75
Steel, for tiebars, re-bars		10,500	210,000,000	2
Lime		3,000	6,000,000	2
Polydrate		1,500	3,000,000	

*For equal quantities of binder this is equivalent to 740,000 BTU/ton. Assumes 65 percent residual asphalt.

**For equal quantities of binder this is equivalent to 750,000 BTU/ton. Assumes 80 percent residual asphalt.

Metric Conversion:

1 BTU/gal = 278.7 J/l

1 BTU/lb = 2324 J/kg

1 BTU/ton = 1.164 J/kg

Table 34. Energy Associated with Aggregate Production

PRODUCT	OPERATION	ENERGY REQUIREMENT			REF.
		BTU/LB	BTU/TON	BTU/YD^3*	
Crushed Stone	Drilling and shooting	6	12,000	21,000	2
	Crushing	25.5	51,000	89,500	2
	Handling (cranes and and bulldozers)	3.5	7,000	12,300	2
	Total	35	70,000	123,000	2
	Total	26	52,000	91,300	76
Crushed Gravel	Crushing	17.5	35,000	61,400	2
	Handling (cranes and bulldozers)	2.5	5,000	8,780	2
	Total	20	40,000	70,000	2
Natural or Uncrushed Aggregate	Total	7.5	15,000	26,300	2

*130 lbs/ft^3 assumed unit weight (2100 km/m^3)

Metric Conversion:

1 BTU/lb = 2324 J/kg

1 BTU/ton = 1.164 J/kg

1 BTU/yd^3 = 1381 J/m^3

Table 35. Energy Associated with Asphalt Concrete Production*

OPERATION	ENERGY REQUIREMENTS			
	BTU/TON OF MIX	BTU/OF OPERATION**	EQUIV. GAL. DIESEL/HR	EQUIV. GAL. DIESEL/TON OF MIX
Asphalt Heating & Storage	6,000	960,000	6.9	0.046
Loader	4,380	657,000	4.7	0.031
Cold Bins, Vibrators, Belt Feeders	100	15,000	0.1	0.001
Cold Feed Belt Conveyor	250	37,500	0.3	0.002
Cold Feed Total	4,730	710,000	5.1	0.034
Dryer Drive Motor	1,260	188,000	1.3	0.009
Dryer Fuel Pump Blower	1,460	218,000	1.5	0.010
Dryer Exhaust Fan	1,260	189,000	1.4	0.009
Dryer Secondary Dust Collector	800	120,000	0.9	0.006
Dryer Total	4,780	715,000	5.1	0.034
Mixing Plant Hot Elevator	350	53,000	0.4	0.003
Mix. Pl. Screening	455	68,300	0.5	0.003
Mix. Pl. Asphalt Pump	250	37,500	0.3	0.002
Mix. Pl. Mineral Filler Elevator	200	30,000	0.2	0.001
Mix. Pl. Pugmill	2,070	310,000	2.2	0.015
Mix. Pl. Compressor (Discharge)	200	30,000	0.2	0.001
Mix. Pl. Storage Conveyor	400	60,000	0.4	0.003
Mix. Pl. Total	3,920	589,000	4.2	0.028
Drying and Heating Aggregate	233,000***	35,000,000	252	1.68
Plant Operation Total	253,000	38,000,000	273	1.82
Paving Machine	4,170	625,000	4.5	0.030
Rollers--3	12,500	1,880,000	13.5	0.090
Spreading and Compaction Total	16,700	2,500,000	18.02	0.120
Drying and Heating Aggregate	278,000$^{\phi}$(3)	41,700,000	300	2.00
Drying and Heating Aggregate	278,000$^{\phi}$(22)	41,700,000	300	2.00
Drying and Heating Aggregate	327,000****	49,000,000	353	2.35
Plant Operation (excluding drying) Lay & Compact	41,700(3)	6,260,000	45	0.300
Plant Operation (excluding drying) Lay & Compact	40,910	6,140,000	44.1	0.30

After reference $^{\phi}$14 except where noted.

*Operating at 67 percent rated power.

**Operating at 150 ton/hr (907 kg/hr).

***5% moisture removed and raise temperature to 300°F (148°C) for a mix which contains 94% by wt. of aggregate.

****Unpublished Illinois source stated in ref. $^{\phi}$14. Data from Illinois quoted in ref. $^{\phi}$14.

Metric Conversion:

1 BTU/ton = 1.164 J/kg

1 gal/hr = 3.785 l/hr

1 BTU/hr = 1055 J/hr

1 gal/ton = 4.173 l/g

Table 36. Energy Associated with Portland Cement Concrete Production

	ENERGY REQUIREMENTS			
			EQUIVALENT GAL. OF DIESEL PER	
OPERATION	BTU TON TON OF MIX	BTU/YD^3 OF MIX*	TON OF MIX	YD^3 OF MIX
Loader	4,380	8,870	0.032	0.065
Conveyor	270	550	0.001	0.003
Mixing and Other Plant Operations	1,770	3,580	0.013	0.026
Total Plant Operation	6,420	13,000	0.046	0.094
Placing, Consolidation and Finishing	2,590	5,240	0.019	0.038

*150 lb/ft^3 (2400 kg/m^3) assumed unit weight (after reference 2)

Metric Conversion:

1 BTU/ton = 1.164 J/kg

1 BTU/yd^3 = 1.381 J/m^3

1 gal/ton = 0.00417 l/kg

1 gal/yd^3 = 4.951 l/m^3

Table 37. Representative Energy Requirements for Maintenance and Rehabilitation Activities (2,77,78)

MAINTENANCE ACTIVITY	ENERGY/UNIT	ENERGY REQUIREMENTS				PERCENT OF TOTAL PAVEMENT AREA TREATED & OTHER ASSUMPTIONS
		BTU/YD² OF AREA TREATED	BTU/YD²	BTU/LANE MI*	BTU/YD²	
Fog Seal - Partial Width	10,500 BTU/gal	1,050		3,700,000	525	50 percent
	12,100 BTU/gal	1,120		3,950,000	560	
Fog Seal - Full Width	6,850,000 BTU/lane mi	970		6,850,000	970	100 percent
	3,300,000 BTU/lane mi	470		3,300,000	470	
Chip Seal - Partial	537,000 BTU/yd²	8,200		8,660,000	1,230	
	1,100,000 BTU/yd²	9,210		9,725,000	1,380	
	1,000,000 BTU/yd²	6,000		6,300,000	900	
	1,630,000 BTU/yd²	7,500		7,930,000	1,130	
	1,160,000 BTU/yd²	8,100		8,600,000	1,210	
Chip Seal - Full Width	30,700,000 BTU/lane mi	4,360		30,700,000	4,360	100 percent
	27,800,000 BTU/lane mi	3,950		27,800,000	3,950	
Surface Patch - Hand Method	1,700,000 BTU/yd³	45,000	45,000	8,000,000	1,140	2.5 percent
	3,210,000 BTU/yd³	89,300	89,300	15,700,000	2,260	1 in. thick
Surface Patch - Machine Method	880,000 BTU/yd³	24,500	24,500	17,200,000	2,450	10 percent
	1,070,000 BTU/yd³	29,800	29,500	21,000,000	2,990	1 in. thick
	1,190,000 BTU/yd³	33,085	33,085	23,300,000	3,300	
Digout & Repair Hand Method	1,600,000 BTU/yd³	178,000	44,460	25,000,000	3,560	2 percent 4 in. thick
Digout & Repair Machine Method	1,120,000 BTU/yd³	187,000	31,200	65,800,000	9,350	5 percent
	810,000 BTU/yd³	135,000	22,500	47,500,000	6,750	6 in. thick
Crack Pouring	32,700 BTU/gal			8,500,000	1,220	250 lin. ft.
	60,670 BTU/gal			16,020,000	2,280	per station
	33,500 BTU/gal			8,700,000	1,230	50 lin. ft/gal
	29,300 BTU/gal			7,600,000	1,080	
Slurry Seal	9,400,000 BTU/lane mi	1,340		9,400,000	1,340	100 percent
Asphalt Concrete Overlay	512,000 BTU/ton	55,600	27,800	391,000,000	55,600	100 percent
	533,000 BTU/ton	57,800	28,900	407,000,000	57,800	2 in. thick

*Energy requirements for yd² of total pavement surface maintained. For example, surface patching by the hand method may have been applied over only 5 percent to total pavement surface area, yet energy reported is for the pavement area maintained on one lane mi. of pavement.

(25) Indicates reference on which data is based.

Metric Conversion:

1 BTU/gal = 278.7 J/l
1 BTU/gal = 1.164 J/kg
1 in. = 2.54 cm
1 BTU/mi = 656.1 J/km
1 BTU/yd² = 1263 J/m²
1 ft. = .305 m
1 BTU/yd³ = 1.381 J/m³
1 BTU/yd²in = 497 J/m²cm

Table 38. Energy Consumption for Pavement Materials In-Place*

MATERIAL	ENERGY REQUIREMENT			REF.
	BTU/TON	BTU/YD^3	BTU/YD^{2}IN.	
	512,000	1,000,000	27,800	(2)
Asphalt Concrete	533,000	1,040,000	29,000	
PCC-Jointed Non-Reinforced	990,000	2,000,000	55,500	(80)
PCC-Jointed Non-Reinforced	1,210,000	2,450,000	68,000	(2)
PCC-Jointed Reinforced	1,390,000	2,820,000	78,400	(2)
PCC-Continuously Reinforced	1,620,000	3,280,000	91,110	(2)
Slurry Seal			1,340**	
Chip Seal - Emulsion and Crushed Stone			3,950**	(2)
Fog Seal			470**	(2)
Crushed Stone Base	236,000	414,000	11,500	(2)
	218,000	382,000	10,000	(76)
Emulsified Asphalt Base	300,000	562,000	15,600	(2)
Cement-Stabilized Base	600,000	1,100,000	30,500	
Polyhydrate - Fly Ash Base	325,000	605,000	16,800	
Cement-Treated Subgrade	526,000	852,000	23,700	(79)
Lime - Fly Ash	385,000	720,000	20,000	
Lime-Stabilized Subgrade	526,000	852,000	23,700	

*Includes energy associated with manufacturing, mixing, hauling, placing, and compacting.

**These treatments are not 1 in. in thickness.

Metric Conversion: 1 BTU/ton = 1.164 J/kg 1 BTU/yd^{2}in. = 497 J/m^{2}cm
1 BTU/yd^3 = 1.381 J/m^3 1 in. = 2.54 cm

10. Slurry Seal

11. Asphalt Concrete overlay

Energy required for material manufacture, material transportation, mixture production, mixture transportation, mixture placement, and compaction is included in the data reported in Table 37. Assumptions as to the percent of the pavement area treated with the particular maintenance activity and the thickness or quantity of material applied are identical to those used for estimating rehabilitation and maintenance costs (Appendix C). These data were developed based primarily on information obtained from the states of Arizona, Nevada, and North Dakota.

Construction Activities

Energy consumption for materials utilized in pavements (in-place) are given on Table 38. Materials included in the table are asphalt concrete, portland cement concrete, slurry seal, chip seal, fog seal, crushed stone base, and emulsified asphalt base. The energy consumed included the energy associated with manufacturing, mixing, hauling, placing, and compacting. Haul distances for these calculations are of the order of 10 to 30 miles. Requirements for miscellaneous construction operations are shown on Table 39.

Example Problem

The example problem presented in Appendix C and associated with basic economic analysis techniques will be utilized to illustrate how energy data can be used to forecast energy requirements of pavements over a twenty-year period. Two pavement sections were suggested for the roadway. Plan 1 consists of construction of a pavement containing 6 inches of lime stabilized subgrade, 8 inches of crushed stone base, and 2 inches of asphalt concrete surfacing. Overlays are scheduled on a 7-year cycle. Plan 2 consists of constructing a pavement containing 6 inches of lime stabilized subgrade, 8 inches of asphalt treated base, and 2 inches of asphalt concrete. Overlays will not be required during the 20-year life cycle.

The following energy requirements were utilized for the initial construction.

1. Lime stabilization - 14,000 Btu per yd^2-in.
2. Asphalt stabilization (emulsion) - 15,600 Btu per yd^2-in.
3. Crushed stone base - 11,000 Btu per yd^2-in.
4. Asphalt concrete - 28,000 Btu per yd^2-in.

Table 39. Energy Requirements for Miscellaneous Construction Operations

OPERATION*	ENERGY REQUIREMENT				
	BTU/GAL	BTU/TON	BTU/YD^3	EQUIVALENT GALLONS OF DIESEL PER	
				TON	YD^3
Spreading and compaction Granular and Stabilized Based		17,000	30,980	0.122	0.223
Travel Plant Mixing in Windrow		3,000	5,470	0.022	0.039
Blade Mixing		7,820	14,250	0.056	0.103
Central Plant Mixing of Stabilized Base		6,890	12,550	0.050	0.090
Excavation - Earth		39,890	59,100	0.286	
Excavation - Rock		35,500	76,700		
Excavation - Other		39,100	68,700		
Asphalt Distribution, Asphalt Cement	590				
Asphalt Distribution, Cutback Asphalt	445				
Asphalt Distribution, Emulsified Asphalt	145				
Aggregate Spreading for Seal Coats	9.4**				
Rolling Cold Asphalt Mixes	120***				

*135 lb/ft^3 (2160 kg/m^3) assumed unit weight except for excavation items.

**9.4 BTU/yd^2

***120 BTU/yd^2 in.

Metric Conversion: 1 BTU/gal = 278.7 J/l 1 BTU/ton = 1.162 J/kg
1 BTU/yd^3 = 1.381 J/m^3 1 ton = 907 kg 1 yd^3 = 0.764 J m^3
1 in. = 2.54 cm

Energy associated with maintenance operations was based on data from Table 37 for crack sealing operations. Table 40 summarizes energy requirements for the two pavements over a 20-year life. Plan 1 has a lower initial energy requirement while Plan 2 has the lower energy requirement for the 20-year life of the pavement.

Table 40. Energy Associated with Plan 1 and Plan 2 Alternative Pavements

YEAR	BTU'S PER YD^2	
	PLAN 1	PLAN 2
Initial energy	228,000	265,000
1		
2		
3	800	
4	1,000	
5	1,200	
6	1,200	
7	56,000	
8		800
9		
10	800	1,000
11	1,000	
12	1,200	1,200
13	1,200	
14	56,000	1,200
15		
16		1,200
17	800	
18	1,000	1,200
19	1,200	
20	1,200	1,200
TOTAL	352,600	272,800

1 Btu = 1055 J

1 $yd^2 = 8.36 \times 10^{-1}\ m^2$

* U. S. GOVERNMENT PRINTINF OFFICE 1982 361-428/2159

ERRATA

Soil Stabilization in Pavement Structures
A User's Manual

Volume 1

page 7, line 37:	"Unitied" should read Unified
page 10, line 16:	Unified Soil Classification Systems insert classification
page 18, line 14:	0.17 should read 0.07
page 21, line 12:	"...materials et" should read materials wet
page 29, lines 2,4,7:	Volume 1 should read Volume 2
page 29, line 23:	ELSYME should read ELSYM5
page 34, lines 9, 11, 12, 18:	Volume 1 should read Volume 2
page 38, line 15:	"appexoimate should read approximate
page 69, line 15:	add "(" before Figure 33
page 73, line 22:	add comma after rollers
page 76, line 14:	"wetback" should read cutback
page 93, line 10:	eliminate "Volume 2"
page 93, line 36:	eliminate "(Volume 1, Chapter IV)"
page 96, line 2:	eliminate "(see Chapter...)"
page 98, line 12:	It is important that first... add that
page 101, lines 14, 15, 17, 25:	Volume 1 should read Volume 2
page 103, lines 6, 8, 30:	Volume 1 should read Volume 2
page 104, line 3:	eliminate "(reference)"

(See back for Vol. 2)

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