Stone Mastic Asphalt (SMA) Mixture Design

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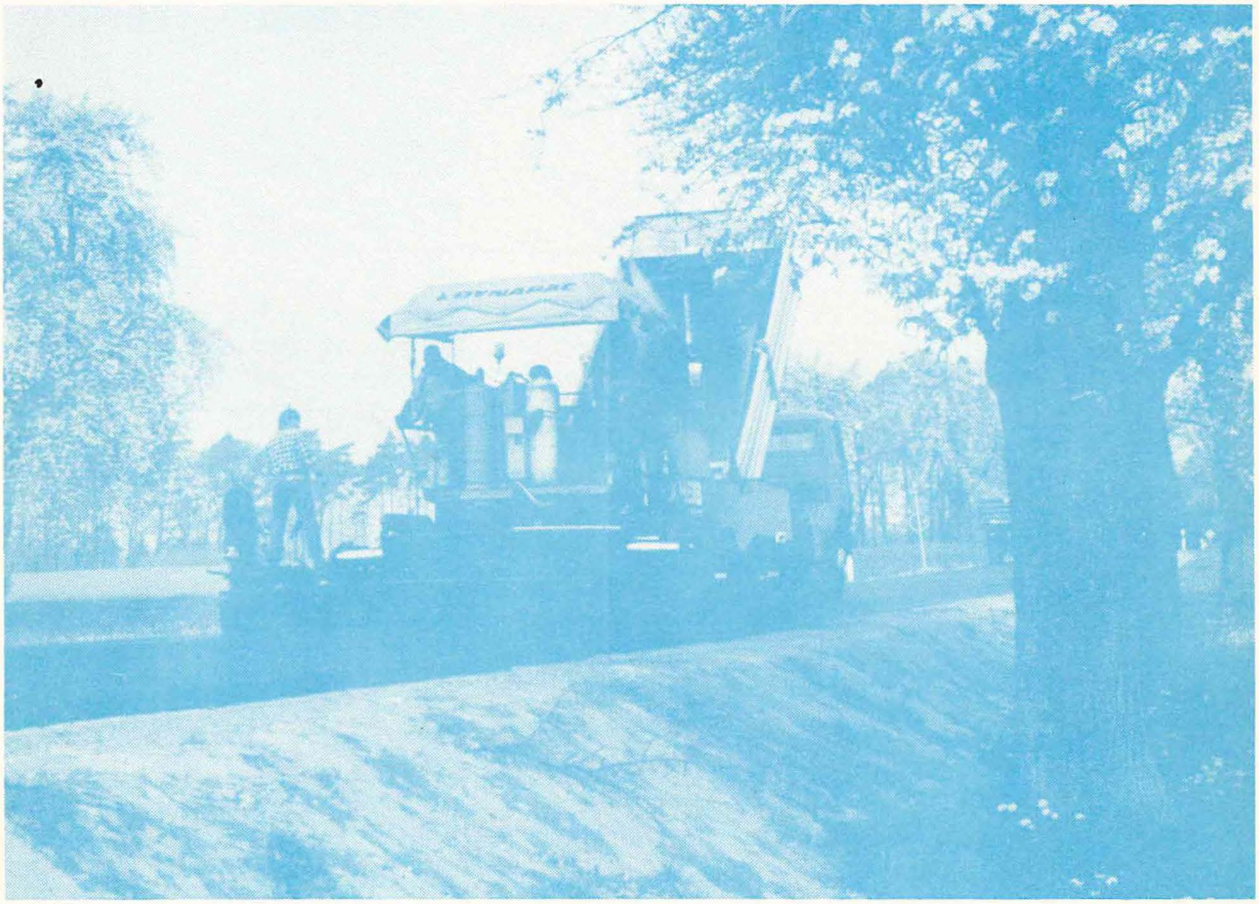

U.S. Department of Transportation

Federal Highway Administration

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

FOREWORD

Participants of the September 1990 European Asphalt Study Tour (EAST) recommended that several European practices dealing with asphalt pavement technology be evaluated in the United States. Those practices recommended for evaluation were lane rentals; contractors' guarantee of work; evaluation of asphalt mixtures using laboratory rut-testing devices and other unique equipment; and the use of customized pavements and materials, such as modified binders, porous asphalt pavements, and stone mastic asphalt (SMA) pavements. The Federal Highway Administration (FHWA) has the responsibility of evaluating, promoting, and transferring European asphalt pavement technology to the United States. The Pavements Division (HNR-20) is assisting with evaluating SMA mixtures and laboratory testing equipment for asphalt mixtures. This report is concerned with the design of SMA mixtures.

Sufficient copies of this report are being distributed to provide two copies to each FHWA Regional Office and three copies to each FHWA Division Office and each State highway agency. Direct distribution is being made to the Division Offices. Additional copies for the public are available from the National Technical Information Service (NTIS), U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

Thomas J Pasko Jr

Thomas J. Pasko, Jr., P.E.
Director, Office of Engineering
and Highway Operations
Research and Development

NOTICE

Technical Report Documentation Page

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16. Abstract

The first objective of this report is to document SMA mixture design information obtained from Europe. Participants of the September 1990 European Asphalt Study Tour (EAST) recommended that SMA pavement technology be evaluated in the United States. The Federal Highway Administration (FHWA) has the responsibility of evaluating, promoting, and transferring this technology.

The second objective is to document SMA mixture design work performed by the FHWA for the Georgia Department of Transportation (GDOT). GDOT placed SMA experimental pavement sections on Interstate 85, north of Route 53, in Jackson County, GA, during July and September of 1991. The mixture designs were performed by the FHWA to supplement GDOT's mixture design work.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

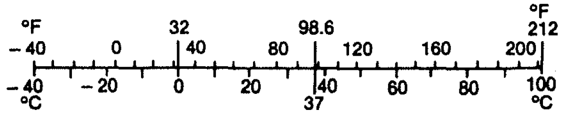
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in²	square inches	645.2	millimetres squared	mm²
ft²	square feet	0.093	metres squared	m²
yd²	square yards	0.836	metres squared	m²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	kilometres squared	km²
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft³	cubic feet	0.028	metres cubed	m³
yd³	cubic yards	0.765	metres cubed	m³

NOTE: Volumes greater than 1000 L shall be shown in m³.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm²	millimetres squared	0.0016	square inches	in²
m²	metres squared	10.764	square feet	ft²
ha	hectares	2.47	acres	ac
km²	kilometres squared	0.386	square miles	mi²
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m³	metres cubed	35.315	cubic feet	ft³
m³	metres cubed	1.308	cubic yards	yd³
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

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CHAPTER 1: MIXTURE DESIGN PRINCIPLES

Chapter 1 documents mixture design information for stone mastic asphalts (SMA). Chapter 2 documents SMA mixture design work performed by the Federal Highway Administration (FHWA) for the Georgia Department of Transportation (GDOT). This work was performed in the Bituminous Mixtures Laboratory located at the Turner-Fairbank Highway Research Center (TFHRC) in McLean, VA.

The information presented in this chapter was primarily obtained from sources in Sweden and Germany. SMA mixtures are used by these countries to decrease the amount of rutting in pavement surface courses subjected to any traffic level. They are also used in Sweden to decrease surface wear from studded tires. SMA mixtures are placed on stable binder and base layers. They will not prevent rutting in these layers. They are called splittmastix-asphalts in Germany, and HABS in Sweden, which translates to hot-mix asphalt with extra stone content. There are also trademarked names such as Viacotop and Stabinor in Sweden.

The principle behind an SMA mixture is to have a higher percentage of coarse aggregate in the mixture compared to a dense-graded mixture in order to obtain greater stone-on-stone contact. Stone-on-stone contact provides a high resistance to permanent deformation, or rutting, and should reduce the dependency of this property on the type and amount of binder. SMA mixtures have a high proportion of high quality coarse, crushed aggregate (stone), a high proportion of binder and mineral filler including minus #200 dust (mastic), a low proportion of middle-sized aggregate, and generally a stabilizing additive to prevent drainage of the binder and mineral filler before the mixture is placed and can cool. SMA mixtures are a type of gap-graded mixture and are designed so that they are both stable and workable. Figures 1 and 2 show a dense-graded mixture and an SMA mixture which were compacted in the Bituminous Mixtures Laboratory.

There is no generic definition for an SMA mixture. SMA gradations have a certain shape when plotted, but the gradations vary slightly in Europe from country to country. Required minimum binder contents also vary. As discussed in this chapter, minimum binder contents are used to improve the durability of the mixture, and to control the shape of the aggregate gradation.

1. Aggregate Properties

a. Aggregate Gradation

The aggregate gradation for SMA mixtures is more open on the coarse side of the maximum density line on the 0.45 power chart compared to dense-graded mixtures. This increases the coarse aggregate stone-on-stone contact. Generally, 20 to 40 percent of the aggregate passes the #4 sieve and 15 to 35 percent passes the #8 sieve. These numbers vary depending on the maximum aggregate size. Aggregates used in open-graded mixtures in the U.S. having a 0.5-in (12.5-mm) maximum aggregate size generally have 30 to 50 percent passing the #4 sieve and 5 to 15 percent passing the #8 sieve. Unlike an open-graded mixture, the majority of the voids between the coarse aggregates in an SMA mixture is filled with mineral filler and binder. Thus, more aggregate is retained on the #8 through #200 sieves with SMA mixtures.

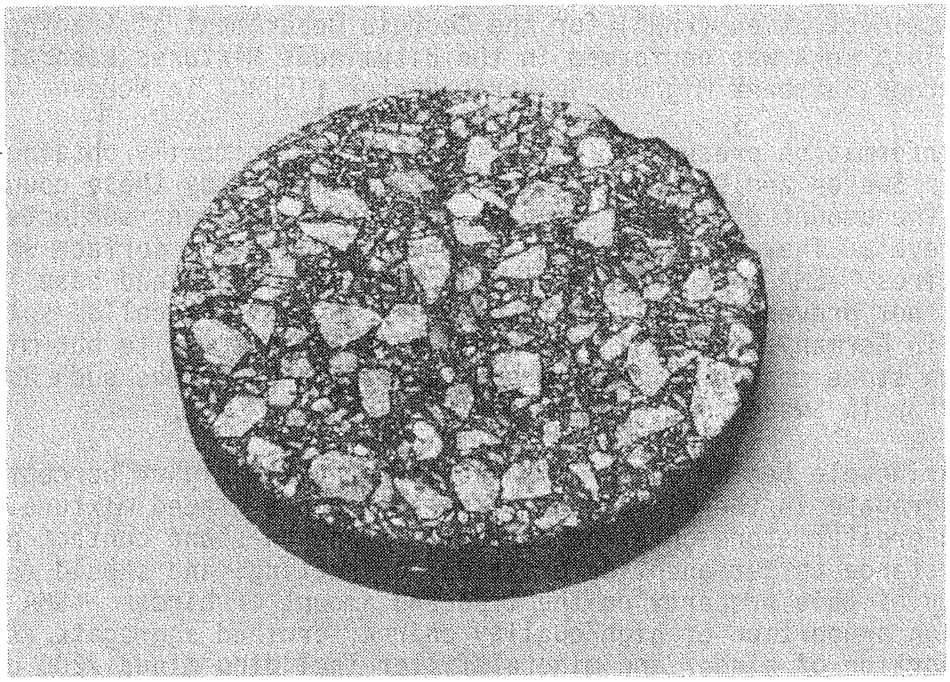


Figure 1. Typical dense-graded mixture with up to 1/2-in (12.5-mm) aggregate.

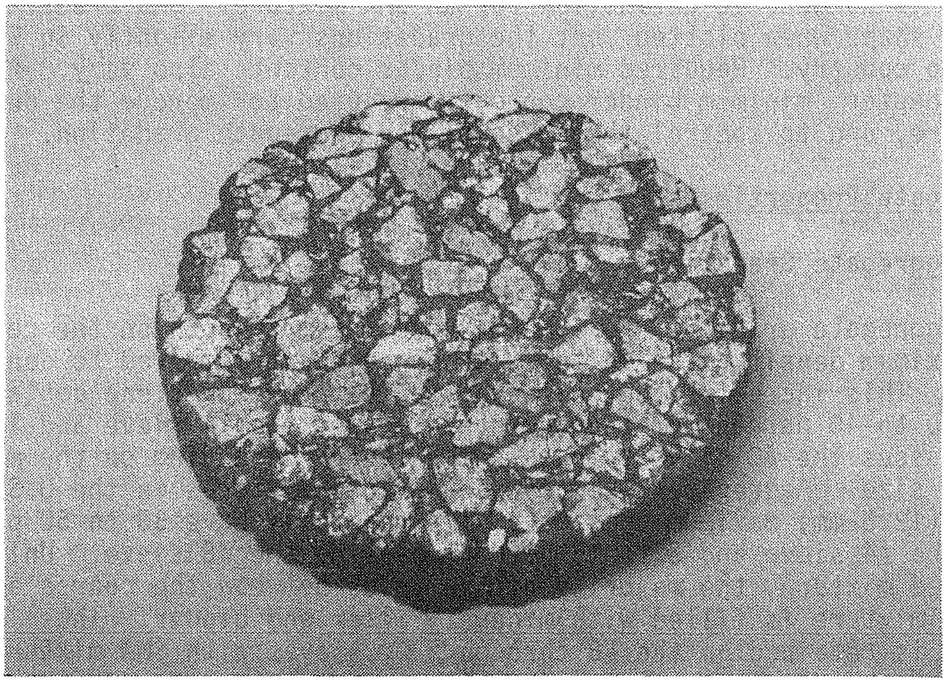


Figure 2. Typical SMA mixture with up to 1/2-in (12.5-mm) aggregate.

European master grading limits for SMA aggregates are fairly liberal, or wide. The Germans have indicated that both an acceptable or a nonacceptable SMA mixture can be produced within their limits. In most cases, the contractors develop the job mix formula (JMF) gradation based on their experiences and also the narrower JMF gradation tolerances. This practice is similar to practices in the U.S., such as in American Society for Testing and Materials (ASTM) D 3515, entitled "Hot-Mix, Hot-Laid Bituminous Paving Mixtures," where the JMF tolerances are narrower than the master grading limits.(1) It is dissimilar to U.S. practices in that the contractors often develop the gradations and tolerances to ensure a certain quality mixture. These European contractors must guarantee the mixture for a certain period of time.

The nominal maximum aggregate sizes used in Sweden are typically 0.445 in (11.3 mm) and 0.625 in (16 mm), which are called SMA 12 and SMA 16, respectively. Five percent aggregate by weight is allowed above the nominal maximum size. Pavement thicknesses are generally 1.3 to 1.7 in (34 to 43 mm) for an SMA 12 and 1.5 to 1.9 in (38 to 47 mm) for an SMA 16.

The nominal maximum aggregate sizes used in Germany are typically 0.197 in (5 mm), 0.312 in (8 mm), and 0.438 in (11.2 mm), which are called SMA 0/5, SMA 0/8, and SMA 0/11, respectively. A smaller nominal maximum aggregate size reduces the level of tire-pavement interaction noise. Ten percent aggregate by weight is allowed above the nominal maximum size. A 0.625-in (16-mm) size or SMA 0/16 was used in the past, but this size has been phased out of the German federal specification for SMA surface mixtures even though dense-graded surface mixtures are produced with this size of aggregate. A few trial pavement sections were also placed using a 0.875-in (22.4-mm) aggregate. A uniform surface texture is difficult to obtain with these larger sized aggregates, and there can be increases in cost and the level of noise. No data are available for these trial sections. Pavement thicknesses are generally around two to four times the nominal maximum aggregate size. The Germans have stated that there is a risk of rutting at intersections if the thickness is more than five times the nominal maximum aggregate size.

The Netherlands uses nominal maximum aggregate sizes similar to Germany. Denmark uses sizes of approximately 0.312 in (8 mm), 0.438 in (11.2 mm), and 0.625 in (16 mm). Norway uses a 0.625-in (16-mm) aggregate, and Finland uses a 0.787-in (20-mm) aggregate, which is large compared to German practices.

Generally, there is approximately 10 percent minus #200 dust in an SMA mixture, and the dust to binder ratio by weight is often around 1.5. This high level of dust can easily be obtained in the laboratory; however, an additional feed system will be needed at the hot-mix plant if it is not capable of adding large amounts of dust or mineral filler. Most plants in the U.S. do not have this capability. No data are available to determine the importance of the gradation of the dust and its effect on extending the binder. Some European contractors have stated that their mineral fillers have less than 20 percent passing 0.000787 in (20 um). Baghouse fines are not used. More information is needed on the properties of the minus #200 materials used in Europe and in the U.S. This critical information is lacking.

Europeans countries use sieve sizes which are different than those used in the U.S. Therefore, master grading limits for U.S. sieves must be developed from European limits after plotting the European limits on U.S. gradation chart paper. This cannot be done arbitrarily because U.S. sieve sizes may only approximate the critical sieve sizes used in Europe to obtain a proper SMA gradation. These critical sizes are close to either the #4 or #8 sieves. When SMA mixtures were first developed in Europe, the aggregate passing the 0.0787-in (2-mm) sieve, or #10 sieve, was tightly controlled. Aggregates below this size were considered the fine aggregate. This sieve size is still used to control the aggregate gradation of many European SMA mixtures.

A set of master grading limits proposed by the author using U.S. sieves is shown in table 1 and figures 3 through 7. These were developed based on the Swedish and German master grading limits. There are slight differences between gradations used by different European countries, although these variations are small compared to the variations for dense-graded mixtures. If the limits in table 1 are used, the gradation will meet either the Swedish or German specifications even though these countries use other sieve sizes.

The author recommends that when a band from table 1 is used, the gradation be near the low end of the band at the #8 sieve (or #10 sieve if this size is used). Most gradations must be as open or gap-graded as possible in order to meet minimum binder content requirements. It is also recommended that until more is learned in the U.S. about SMA gradations and mixtures, an SMA JMF gradation and its tolerances fit as closely as possible inside the master grading band envelope. An exception may be for the nominal maximum aggregate size where the JMF tolerance may slightly exceed the limit given in table 1. This recommendation is intended to reduce the number of possible gradations that can be used in initial SMA projects in the U.S.

b. Percent Crushed Material

In Europe, both the coarse and fine aggregates in SMA mixtures are generally 100 percent crushed materials. Rounded natural sands are only used in limited amounts, generally less than or equal to 10 percent by total aggregate weight. The manufactured to natural sand ratio is always greater than or equal to 50 percent. SMA mixtures are easy to compact in the field and therefore natural sand is not needed to aid workability.

SMA coarse aggregates are generally 100 percent crushed materials. The aggregates do not have rounded surfaces because these may decrease the amount of coarse aggregate interlock. SMA mixtures are high quality mixtures. German specifications require that at least 90 percent of the coarse aggregate be fractured. Rounded aggregates are double crushed. This can be interpreted as requiring two or more mechanically induced fractured faces, but an exact interpretation is not possible. The author recommends that in initial U.S. SMA projects, the coarse aggregates have at least 90 percent particles by weight with two or more mechanically induced fractured faces. Each size fraction above the #4 sieve should be tested. An overall value for the coarse aggregate should be determined based on the proportions of the various coarse aggregate sizes used in the JMF. This requirement is stricter than open-graded mixture specifications used in the U.S., which generally require at least 90 percent of the particles by weight to have one or more mechanically induced fractured face and 75 percent of the particles to have two or more mechanically induced fractured faces.(2) After experience with SMA mixtures is gained in the U.S., it can then be determined whether and how many rounded surfaces can be used.

Table 1. Proposed gradations for U.S. SMA mixtures.

	Percent Passing Each Sieve Size				
	Meets German Specification			Meets Swedish Specification	
Sieve Size	3/4 in	1/2 in	3/8 in	3/4 in	1/2 in
1 in	100			100	
3/4 in	90 - 100	100		95 - 100	100
1/2 in	33 - 66	90 - 100	100	33 - 54	95 - 100
3/8 in	26 - 50	34 - 75	90 - 100	26 - 40	34 - 49
#4	19 - 34	23 - 41	28 - 50	19 - 33	23 - 37
#8	16 - 26	18 - 30	21 - 34	16 - 29	18 - 30
#16	14 - 23	15 - 24	16 - 25	14 - 27	15 - 27
#30	12 - 20	12 - 20	12 - 20	12 - 24	12 - 24
#50	10 - 17	10 - 17	10 - 17	10 - 21	10 - 21
#100	9 - 14	9 - 14	9 - 14	9 - 16	9 - 16
#200	8 - 13	8 - 13	8 - 13	8 - 13	8 - 13

(in)(2.54)=(cm)

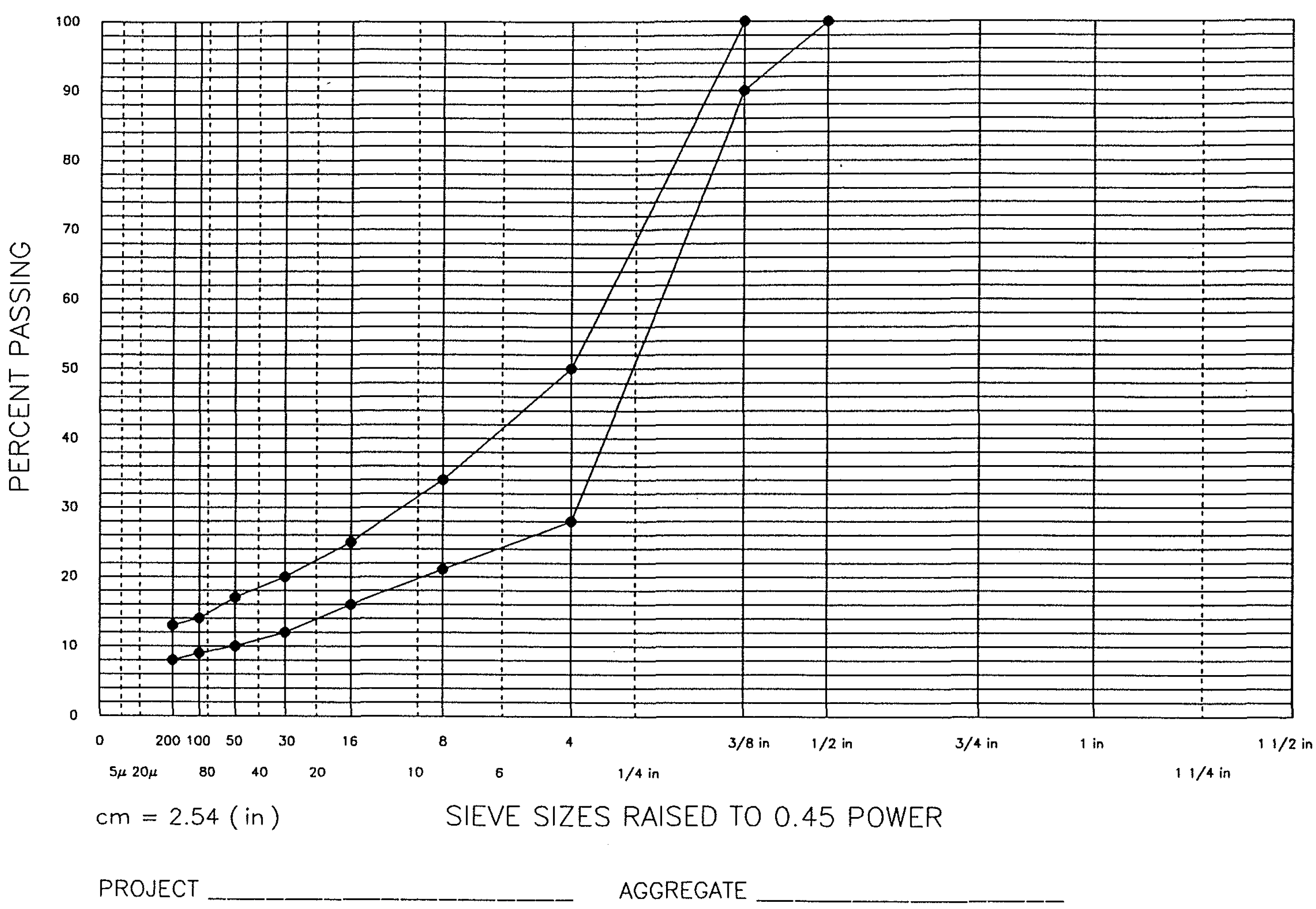


Figure 3. Proposed gradations for U.S. 3/8-in (9.5-mm) SMA mixtures which meet German specifications.

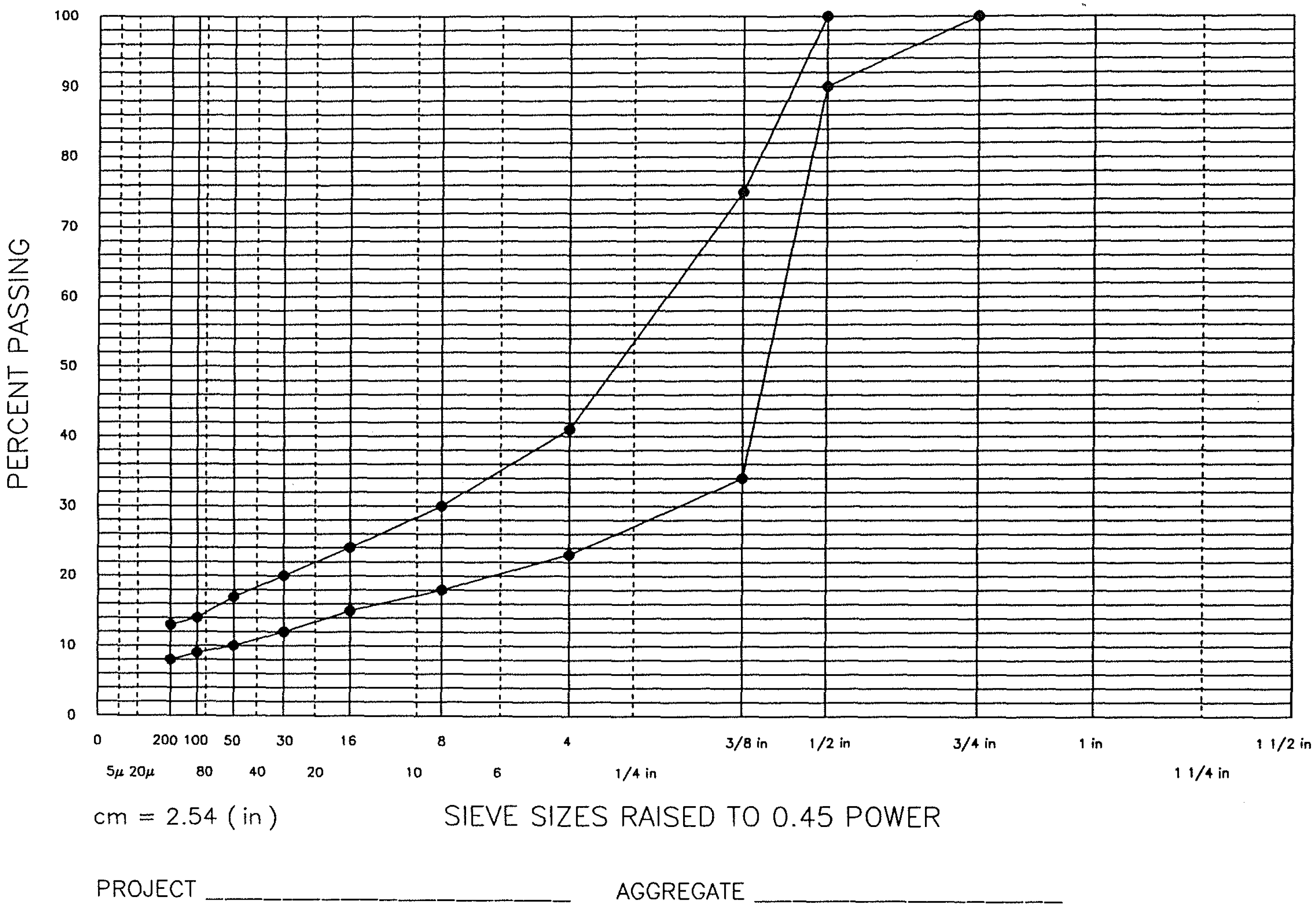


Figure 4. Proposed gradations for U.S. 1/2-in (12.5-mm) SMA mixtures which meet German specifications.

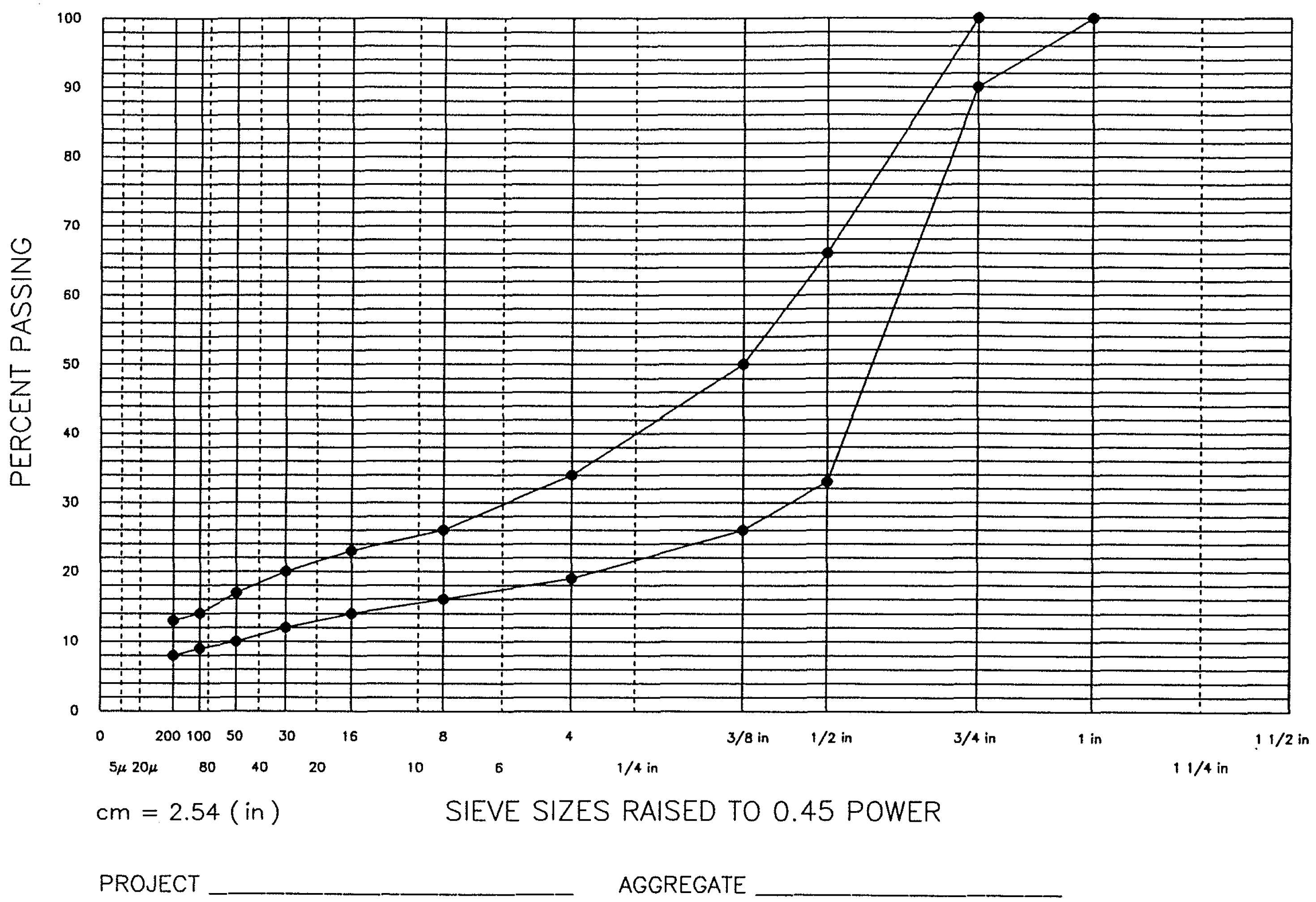
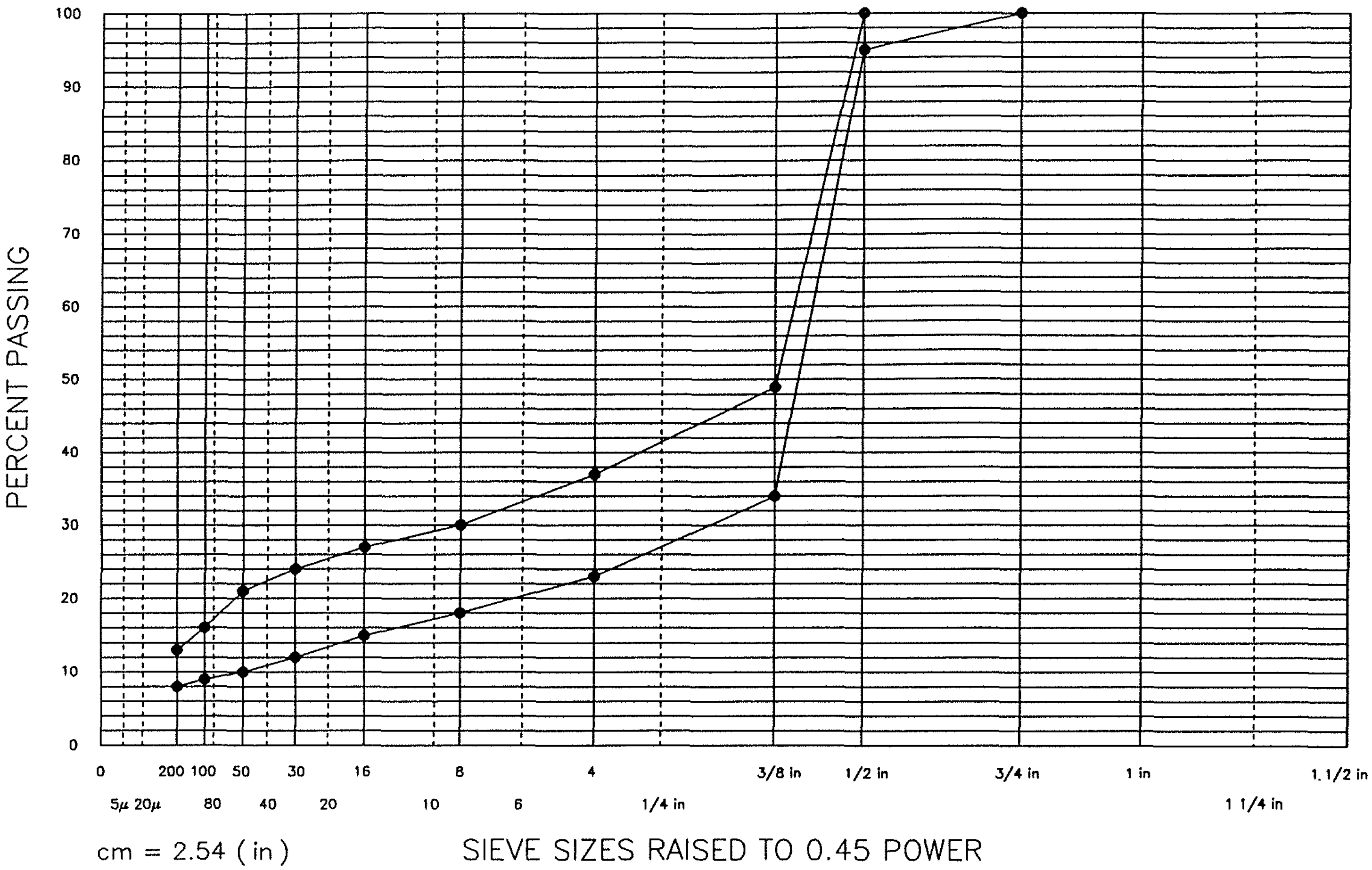


Figure 5. Proposed gradations for U.S. 3/4-in (19.0-mm) SMA mixtures which meet German specifications.



PROJECT ______________________________ AGGREGATE _________________________

Figure 6. Proposed gradations for U.S. 1/2-in (12.5-mm) SMA mixtures which meet Swedish specifications.

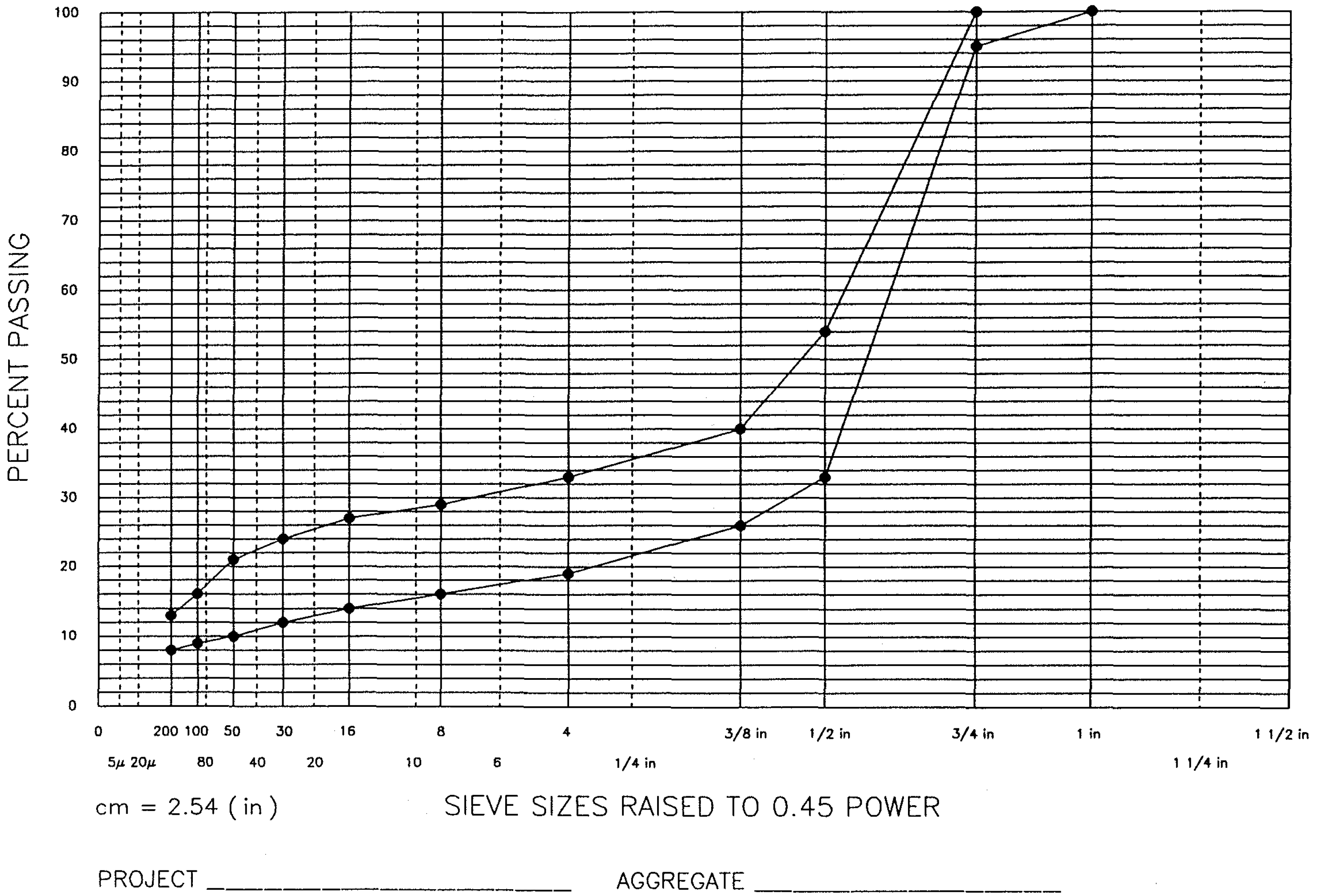


Figure 7. Proposed gradations for U.S. 3/4-in (19.0-mm) SMA mixtures which meet Swedish specifications.

c. Aggregate Durability

Highly durable aggregates are used in Europe. Common coarse aggregates are granite, basalt, gabbro, diabase, gneiss, phorphory, and quartzite. The aggregates must have (1) a highly cubic shape and rough texture to resist rutting and movements, (2) a hardness which can resist fracturing under heavy traffic loads, (3) a high resistance to polishing, and (4) a high resistance to abrasion. This last requirement is extremely important in Sweden where studded tires are allowed. Phorphory and quartzite are commonly used in all types of surface courses in Sweden. Limestone and sandstone coarse aggregates are not used in SMA mixtures in Sweden or Germany, although crushed limestone mineral filler is commonly used.

Aggregate testing is a high priority in Sweden and Germany. The Swedes have (1) surface abrasion machines for both aggregates and mixtures, (2) an impact device to determine the durability of aggregates against fracture, and (3) slotted sieves to determine the shape of the particles. Aggregate specifications in Sweden depend on the level of traffic (high and low). Aggregates in Germany are tested for (1) fracture by impact, (2) fracture by freezing and heat, (3) resistance to expansion or degradation by water, and (4) shape. These European methods are not used in the U.S.; therefore, it may be worthwhile to evaluate them.

SMA aggregates must be as durable as those used in open-graded mixtures. Therefore, the author recommends that the aggregate be polish resistant so that good frictional properties are maintained. Relatively pure carbonate aggregates should not be used because they tend to polish.(2)

The fine aggregates must also be nonplastic to avoid swelling and other moisture-related problems. Tests to be performed are American Association of State Highway and Transportation Officials (AASHTO) Methods T 89, entitled "Determining the Liquid Limit of Soils," and T 90, entitled "Determining the Plastic Limit and Plasticity Index of Soils," or ASTM Method D 4318, entitled "Liquid Limit, Plastic Limit, and Plasticity Index of Soils."(1,3)

Neither Sweden nor Germany perform the Los Angeles abrasion test on aggregates. Therefore, they do not have specifications for this test. The maximum abrasion loss for aggregates used in open-graded mixtures used in the U.S. is generally 40 percent by weight when measured by AASHTO T 96, entitled "Resistance to Abrasion of Small Size Aggregate by Use of the Los Angeles Machine," or ASTM C 131, entitled "Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine."(1,2,3) Whether 40 percent is applicable for aggregates used in SMA mixtures is unknown. The author recommends that this value not be exceeded when testing SMA aggregates.

For dense-graded mixtures in the U.S., the total of all deleterious materials in the aggregate, such as clay lumps and friable particles, should not exceed 1 percent by weight when measured by AASHTO T 112 or ASTM C 142, entitled "Clay lumps and Friable Particles in Aggregates."(1,3,4) The minimum sand equivalent value of the minus #4 sieve material in dense-graded mixtures is 45 when measured by AASHTO T 176, entitled "Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test," or ASTM D 2419, entitled "Sand Equivalent Value of Soils and Fine Aggregate."(1,3,4) Also recommended for dense-graded mixtures is that the sulfate soundness weight loss of the fine aggregate after 5 cycles should not exceed 15 percent when sodium sulfate is used and 20 percent when magnesium sulfate is used. Soundness is measured by AASHTO T 104 or ASTM C 88, entitled "Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate."(1,2) As a minimum, the author recommends that SMA aggregates also meet these requirements.

Most aggregates used in Sweden, Germany, and France for asphalt pavements have low water and binder absorptions, generally below 2 percent. Therefore, short-term or long-term binder absorptions are not reported to be problems. Whether highly absorptive aggregates can be used in SMA mixtures is unknown and needs to be determined.

d. Flat and Elongated Particles

Aggregates used in SMA mixtures, like many other types of mixtures, cannot have excessive numbers of flat and/or elongated particles. In the laboratory, the mixture design data may be erratic because of these particles. For example, the air voids versus binder content relationship may not be a smooth curve as typically obtained. Flat and elongated particles can affect how a mixture compacts because they can break during the mixing and compaction processes and can align themselves during the compaction process. Some may become parallel to the compaction direction, while others remain perpendicular. How they align themselves may possibly interact with the binder demand. Furthermore, the maximum density line on a gradation plot, such as on the 0.45 power chart paper, may not be close to the true maximum density line because these particles can influence how all of the aggregates fit together. The 0.45 power chart is based on aggregates that are close to being cubic.

Flat and elongated particles are also susceptible to breaking during processing and mixing at the hot-mix plant and during field compaction. Particles may also align themselves during the compaction process. This may alter the stability of the mixture or cause bleeding. In many dense-graded mixtures, greater numbers of flat and elongated particles have been found to be more parallel to the pavement surface than randomly distributed.

Definitions for flat and elongated particles are given in ASTM C 125, entitled "Concrete and Concrete Aggregates."(1) Elongated particles have a high length to width ratio. Flat particles have a high width to thickness ratio. The length is the longest dimension of the particle and the thickness is the thinnest dimension. The width is the in-between third dimension. Some particles can be both flat and elongated.

In ASTM D 4791, entitled "Flat or Elongated Particles in Coarse Aggregate," both the percent flat and percent elongated particles are determined.(1) There are some nonstandardized procedures in the U.S. in which the percent flat particles, for example, those shaped like a dime, are not distinguished from the elongated particles. In these procedures, the length to thickness is measured and the total percent elongated and flat particles is reported. This type of procedure is much less time-consuming but will generally give a higher percentage of failing particles compared to the ASTM procedure, even if a total percent flat and elongated particles is calculated using the ASTM results.

Aggregates used in SMA mixtures in Sweden above the 0.157-in (4-mm) sieve, which is the #5 sieve, generally have a Swedish shape factor of 1.40 or less. Typical cubic aggregates used in Sweden have a value of 1.20. To obtain the value, a method based on using slotted sieves of various widths is performed. This method is not used in the U.S., and there are no comparisons to U.S. methods. It appears that the shape factor is based on measuring the number of flat pieces, but the procedure including the use of slotted sieves would have to be tried to determine exactly what this method measures. This procedure is worth investigating.

In Germany, a 3 to 1 length to thickness test is performed on the plus 0.197-in (5-mm) aggregate, which is approximately the plus #4 sieve aggregate. Aggregates having more than 20 percent particles by weight greater than a 3 to 1 ratio are rejected. The Germans have indicated that some elongated and other irregularly shaped particles are desirable because they can improve interlocking and stability, but there are no requirements in this regard. Apparatuses used to perform this test are available in the U.S.

In the U.S., either the percentage of flat and elongated particles is not measured, or it is determined using an apparatus which is set at one particular ratio, or slot size, as in the German test. There are U.S. apparatuses, such as the one shown in ASTM D 4791, which can be adjusted to test different sizes of coarse aggregates while maintaining either the length to width, width to thickness, or length to thickness ratio. A ratio of either 3 to 1 or 5 to 1 is generally used in the U.S. The percentage of failing particles is calculated for the particular ratio chosen. The percentage can be calculated both on a weight basis and on a number of particles basis, but generally a weight basis is used in specifications. Most tests in the U.S. are performed on the plus 3/8-in (9.5-mm) aggregate, but they can also be performed on the #4 to 3/8-in (9.5-mm) aggregate with little problems, although the test is more time-consuming.

A pass/fail criteria for a length to thickness test is often used in the U.S. to reject or accept an aggregate even though this does not follow the ASTM D 4791 procedure. For dense-graded mixtures, an general recommendation is that the total percent flat and elongated particles in the aggregate fraction above the #4 sieve size be less than 30 percent if a 3 to 1 length to thickness specification is used and 5 percent if a 5 to 1 length to thickness is used. This is a "general" recommendation because there are no universally accepted criteria for flat and/or elongated pieces. This is a liberal recommendation compared to the German specification and may be too liberal for mixtures which contain a high amount of coarse aggregate. Coarse aggregates used in gap-graded, coarse mixtures may be more susceptible to breaking in a hot-mix plant operation. (The fine aggregates may provide a cushioning effect in the plant.)

The author recommends that until more is known about the effects of elongated and flat particles on the performances of SMA mixtures, the German test and specification for flat and elongated particles be used. This test is the same or very similar to tests used in the U.S, and the ASTM D 4791 apparatus can be used. ASTM D 4791 procedures can also be used, except that the length to thickness is measured. Each size fraction above the #4 sieve should be tested using a 3 to 1 length to thickness gauge. An overall value for the coarse aggregate should be determined based on the proportions of the various coarse aggregate sizes used in the JMF. A maximum of 20 percent aggregate by weight passing the 3 to 1 test is the limit used in Germany.

2. Bitumen Properties

Bitumens used in Europe are generally 65, 80, or 85 penetration grade asphalts and are from consistent sources. Sweden only uses Venezuelan crudes. A 200 penetration grade asphalt is also used in Germany in some thin layers having a nominal maximum aggregate size of 0.197 in (5 mm). The penetration at 77 °F (25 °C), softening point, and the viscosity at 275 °F (135 °C) are generally measured. Modified binders have been used in some SMA mixtures, but there is little data and no Swedish or German national specifications for these binders when used in SMA mixtures.

Most northern European countries use 80 or 85 penetration grade asphalt. The closest viscosity-graded asphalts would be AC-20 and AC-10. Southern areas of Europe use 65 penetration grade asphalt. This grade is also used in Germany for heavy traffic loads. As in the U.S., the grade of asphalt is based on a compromise between the binder properties needed at low and at high pavement temperatures. There is no apparent reason why highway agencies in the U.S. cannot use their normal grade of binder.

3. Stabilizing Additives

Potential problems with SMA mixtures are (1) drainage or separation of the binder and mineral filler during storage, hauling, and placement, (2) bleeding, and (3) poor skid resistance. Swedish contractors have indicated that storage and placement temperatures generally cannot be lowered to control drainage and bleeding because this will create difficulties with obtaining the required degree of compaction. Therefore, stabilizing agents such as fibers, rubbers, polymers, Lake Trinidad asphalt, carbon black, artificial silica (SiO_2), or combinations of these materials are added to stiffen the mastic at high temperatures and to obtain even higher binder contents for increased durability. Asbestos fibers, which were used at one time, can no longer be used in Sweden, Germany, or the U.S. Most suppliers of stabilizers equate the stiffening of the mastic to improved temperature susceptibility, although the effects of the stabilizer at both high and low temperatures are generally not shown.

Problems with skid resistance are either due to bleeding or to the thick binder films on the aggregates. Crushed sand or aggregate chips, preferably chips precoated with binder, are sometimes spread on the pavement to improve skid resistance until the binder film on the surface of the pavement is worn off. After the coarse aggregates become exposed, SMA mixtures reportedly have very good skid resistances when properly placed.

The degree of drainage and bleeding varies from mixture to mixture. Most problems occur when the binder content is greater than 6 percent, although most mixtures are designed to have at least 6 percent binder. When SMA mixtures were being developed, stabilizers were not used. Binders contents were generally less than 6 percent, and the mixtures were not as gap-graded as today. Current SMA mixtures are reported to have longer lives than the original versions, but there is little documentation. Current SMA principles were developed more than 8 years ago, but minor changes are still being made.

More than 85 percent of the SMA mixtures produced in Sweden and Germany use fibers to prevent drainage and bleeding. The common fibers are cellulose and a natural mineral fiber termed rock wool. The volumes of these two fibers used in Sweden are approximately equal, while around 95 percent of the fiber market in Germany uses cellulose. Most of the rock wool is manufactured in Sweden. Norway uses rock wool while Denmark and the Netherlands use cellulose. The type of fiber or other stabilizer chosen is highly driven by economics. Contractor or government preferences based on concerns other than technical are also factors.

The various fibers used in SMA mixtures have different dimensions. The maximum length of any type of fiber used in an SMA mixture varies, but most are less than 0.2 in (5 mm). There are no generic specifications for fibers such as for length, thickness or diameter, aspect ratio, or for coatings. There are no generic specifications any other stabilizer either, although each manufacturer has their own specification for their product.

Rock wool and cellulose fibers are chemically inert in asphalt whereas rubbers and polymers may not be completely inert. The advantages and disadvantages of using a stabilizing additive which is not inert are unknown. Stabilizers which react or slightly dissolve with an asphalt binder may improve or degrade the properties of the binder in the pavement. These products must be treated and tested for performance like any modified binder. The effects of fibers on the long-term pavement performances of SMA mixtures are unknown, and thus whether and how much they modify a binder are unknown. Fibers are primarily used to prevent drainage and bleeding only.

While there are many types of cellulose fibers, certain types have been developed by European manufacturers specifically for the paving industry. This includes optimizing the dimensions of the fiber, requiring a certain amount of oil absorption, and adding proprietary coatings, possibly, coupling agents. Some cellulose fibers are only 75 to 80 percent cellulose by weight. The adherence of asphalt to cellulose fibers is often low without coatings and/or the fibers swelling.

Potential problems with cellulose fibers are that they can burn when they contact a flame and swell when they contact water. Rock wools will not have these problems, although they can physically breakdown in the hot-mix plant by the grinding action of the aggregate. Cellulose fibers may also breakdown if the mixing time is extremely long, but this problem has been reported by the Europeans using their cellulose fibers. No problems with any fiber drawing moisture into the mixture by acting like wicks have been reported.

Some fibers used in the U.S., generally glassy fibers such as fiber glass, are coated to prevent them from easily breaking down when they rubbed against each other. Often, small amounts of gelatinous substances are used. This process is called sizing. Whether any European fibers used in SMA mixtures are processed in this way is unknown.

Fibers are generally added in amounts from 0.3 to 1.5 percent by weight of the mixture. The needed amount of fiber depends on the properties of the fiber such as thickness and length, how susceptible the mixture is to drainage, and the discharge temperature of the mixture at the hot-mix plant. Dosages of 0.5 to 0.6 percent are common for rock wool. Dosages for cellulose fibers are generally in the range of 0.3 to 0.6 percent, with 0.3 percent being the common dosage. For a given mixture, the needed dosage of cellulose may be slightly lower than the needed dosage for rock wool. Cellulose can hold more binder on an equal weight basis. As the maximum aggregate size decreases, the needed dosage of either fiber decreases. Mixtures with smaller maximum aggregate sizes are apparently less susceptible to drainage even though they often have higher binder contents. Mixtures with a nominal maximum aggregate size at the #4 sieve may only need 0.15 percent fiber. As the hot-mix plant discharge temperature decreases, the needed dosage of either fiber also decreases. Hot-mix plants in the U.S. generally discharge a mixture 40 °F (22 °C) lower on an average than in Sweden and Germany. Therefore, drainage may be a lesser problem and obtaining adequate field compaction a greater problem in the U.S.

Various polymers have also been used to stabilize mixtures in Europe, but as indicated previously, the majority of SMA mixtures in Sweden and Germany contain fibers. The needed amount of polymer depends on the properties of the polymer, how it interact with the asphalt, how susceptible the mixture is to drainage, and the discharge temperature of the mixture at the hot-mix plant. The Netherlands and Norway are prime users of modified binders. Polymers are generally added by weight of the asphalt cement and additions of 5 to 8 percent are common.

Fibers and polymers have been combined in some SMA mixtures in some European countries, but this has only been performed on a limited basis in Sweden and Germany to date. When both are added to the same mixture, the polymer is generally used to improve properties at both high and low temperatures and is not simply used as another stabilizing additive. Several European sources have indicated that the combination of fibers and polymers may provide the best mixture properties, but the cost of the mixture is higher and supportive data is lacking.

Because stabilizing additives control drainage and bleeding, they can often be used to increase the optimal binder content. The gap in the gradation can be further increased and additional binder added while maintaining the air void level. Of course, there will be a limit to this effect, and the master grading limits will control how much a gradation can be changed. Cellulose fibers generally can hold 0.3 percent or more binder than other stabilizers, and therefore can provide the highest binder contents. They can often hold 0.5 to 0.6 percent more binder than many polymer stabilizers. Several European contractors indicated that mixtures containing cellulose fibers require the same amount of compactive effort as mixtures containing other stabilizers even when the percent binder is higher. However, cellulose fibers often require more mixing time at the hot-mix plant.

A part of the greater capacity of cellulose fibers to hold binder has been attributed to the absorption of some binder into the fibers themselves. How much binder is absorbed is unknown. Whether the absorbed binder is of any benefit to the properties of the mixture is also unknown. In Sweden and Germany, any absorbed binder is generally treated as still being a part of the binder, which increases the durability of the mixture against age hardening and moisture damage, and increases the resistance against fatigue cracking.

In Sweden and Germany, SMA mixtures are tested to determine if drainage will be a problem and to determine the amount of stabilizer needed. Not all fibers or polymers effectively stabilize a mixture. Drainage tests have also shown the increased capacity of cellulose fibers to hold binder. A German test procedure is given in appendix A. It was developed based on studies using cellulose fibers. If there is too much drainage, then the amount of cellulose is increased. Correlations between the percent cellulose and the amount of drainage can be established to obtain an optimal dosage. The applicability of this test procedure to other stabilizers is unknown. A procedure which is applicable to various stabilizers is needed because there are no generic specifications for stabilizers.

4. Mixture Design Methodology

The Marshall method of mixture design is used in Sweden and Germany for designing SMA mixtures. Contractors incorporate their experiences with a mixture (dense-graded, open-graded, SMA, etc.) into the design. Parts of these experiences are keep secret from their competitors. National specifications are based on field performance and the results of analyses of material properties such as gradation, binder content, and air voids. Designs and specifications do not include the use of reclaimed asphalt materials.

Stabilizing additives should be incorporated into the mixture in a way which simulates processes at the hot-mix plant. Most stabilizing additives are added to the hot aggregate and dry mixed before the binder is added. However, additives which are not altered by heat and/or whose distribution in the mixture will not depend on plant processes can be added to the aggregate prior to being heated in the oven. Additives such as polymers and fiber-bitumen pellets which are affected by heat must be added in a way which simulates the hot-mix plant as closely as possible. When using loose fibers or fiber-bitumen pellets, the mixing time at the hot-mix plant is increased slightly. Whether and how much additional mixing time is needed in the laboratory is not clearly known. Laboratory and plant mixing actions are different. Excessive mixing times in the laboratory may cause rock wool fibers to break down and should be avoided.

The compaction temperature in the laboratory in Sweden is generally between 293 and 302 °F (145 and 150 °C) and rarely exceeds 311 °F (155 °C). Even so, temperatures up to 338 °F (170 °C) are allowed when a fiber is used as the stabilizing additive. Germany generally uses a temperature of 275 °F (135 °C). Neither loose mixtures nor compacted specimens are cured in an oven in either country.

A 50-blow Marshall design is used, and the Swedes and the Germans to date are satisfied with this type of compaction and compactive effort. Increasing the number of blows is not recommended by them because this may increase the number of fractured aggregates with little to no increase in density. All optimal binder contents reported by the Swedes and Germans and minimum binder contents contained in their specifications were obtained through a 50-blow Marshall compactive effort. Automatic Marshall hammers are generally used. Other methods of compaction, such as gyratory, kneading, and rolling wheel may provide other optimal binder contents based on a constant air void level.(5) These binder contents may not meet the minimum binder content requirements set by these countries. If the compactive effort is greater than that of the 50-blow Marshall hammer, then at equal air void levels, the binder contents will be lower.

Stability and flow specifications for dense-graded mixtures can be used for SMA mixtures. However, because of the high amount of coarse aggregate in an SMA mixture, the Marshall trace often does not have a well-defined peak. In some cases, the peak may occur at a very high flow, which is off the standard Marshall chart paper of many Marshall testing machines. Therefore, stabilities and flows may not always be obtained. The Marshall method of compaction is used in Europe, but often the stabilities and flows are not used. Many designs are based on air void levels and minimum binder contents.

An air voids analysis is performed in Sweden and Germany as in the U.S. Design air void levels are often slightly lower than those used for dense-graded mixtures. The high stone-on-stone contact allows the use of lower air void levels. There are no voids in the mineral aggregate (VMA) or voids filled (VF) requirements, but these properties are generally above 16.5 percent and 78 percent, respectively, for a nominal maximum aggregate size of 0.5 in (12.5 mm).

The Swedes indicate that there is little change in stability across a design air void range of 2 to 5 percent. However, based on their field experiences, mixtures should not be designed near the 2-percent air void level when stability is the primary concern. For good stability, a 3- to 4-percent range would be better than a 2- to 3-percent range. The 2- to 3-percent range is better for increased resistance against studded tire wear. This range is usually used in Sweden because their major problem is studded tire wear. SMA mixtures in Sweden are generally designed close to the 3-percent air void level for high traffic pavements and close to the 2-percent air void level for low traffic pavements. SMA mixtures in Germany are generally designed at a 3-percent air void level with a tolerance of 2- to 4-percent. As with dense-graded mixtures, excessive binder contents due to low design air void levels, somewhere below 2 percent, will decrease the performance of the mixture. Excessive binder or mastic will reduce the stone-to-stone contact.

The German federal specification requires a binder content of 6.5 to 7.5 percent by mixture weight for SMA mixtures with nominal maximum aggregate sizes of 0.312 in (8 mm) or larger, and 7.0 to 8.0 percent for SMA mixtures with a nominal maximum aggregate size of 0.197 in (5 mm). If the minimum binder content cannot be obtained at the 3-percent design air void level, then the gap in the gradation has to be further increased to obtain more VMA. The binder content should then increase when the mixture is redesigned. The above minimum binder contents may be increased in 1992.

The German specification was developed using cellulose fibers. There are no specifications for binder contents in Germany when using stabilizers other than cellulose. Other stabilizers generally do not absorb and hold as much binder, and thus it is more difficult to obtain high binder contents. Optimal binder contents for SMA mixtures using stabilizers other than cellulose are almost always lower than those which use cellulose, and often they do not meet the German federal specification. Other stabilizers often can only provide 6.0 to 6.3 percent binder at a 3-percent design air void level.

Whether the higher binder contents provided by cellulose are needed for increased durability or increased stone-on-stone contact is unknown. However, when there is no minimum binder content or other strict means of controlling the gradation, such a mechanical test measurement, it is difficult to know whether the chosen gradation will provide the desired properties. Because of this, the author recommends that a gradation chosen using table 1 be near the low end of the band at the #8 sieve (or the #10 sieve if this size is used). This should provide high stone-on-stone contact, a high VMA, and a high binder content.

Target binder contents of 6.6 percent for an SMA 12 and 6.3 percent for an SMA 16 are recommended in Sweden. However, actual binder contents are generally slightly lower than the 6.5 percent level required in Germany. Binder contents in France are typically between 6.3 and 6.8 percent. As a preliminary guide for U.S. SMA mixtures, the author recommends that the binder content be a minimum of 6.3 percent at a 3-percent design air void level when absorptive cellulose fibers are used and 6.0 percent for other stabilizers. The author again recommends that a gradation chosen using table 1 be near the low end of the band at the #8 sieve (or the #10 sieve if this size is used). Important to this recommendation concerning the minimum binder content is the characteristics of the mineral filler used. If mineral fillers used in U.S. have more material smaller than 0.00079 in (20 um) than in Europe, it may be more difficult to obtain these recommended binder contents.

SMA mixtures have higher binder contents compared to those for dense-graded mixtures having the same nominal maximum aggregate size and type of aggregate. The higher binder contents and lower air void levels may help to resist age hardening, moisture damage, and fatigue cracking, but field performance and laboratory data needed to firmly establish this hypothesis is limited. Promoters of cellulose fibers, which can provide higher binder contents compared to most other stabilizers, emphasize the positive aspects of higher binder contents and increased film thickness.

Like open-graded mixtures, SMA mixtures may appear rich in binder. Binder contents should not be reduced solely because of this appearance. Even small amounts of bleeding are often eliminated by using additional stabilizing additive.

The air void level in an SMA pavement layer after compaction by rollers is lower than for a dense-graded mixture having the same type of aggregate and maximum aggregate size. The Swedes and Germans report that field air void levels are typically 3 to 5 percent and are specified to be less than 6 percent. When the design air void level is 3 percent, mixtures with fibers often compact to a 3- to 4-percent level. Close to 100 percent compaction based on the design air void level is often obtained. They also state that SMA mixtures at their ultimate or refusal density after traffic will not have air void levels significantly lower than the design level. If true, and because cubic aggregates which do not orientate under compaction are used, then the 50-blow Marshall hammer provides adequate compaction. The Swedes and Germans have also stated that initial field air levels for SMA mixtures containing polymers may be slightly higher than for fibers. Verification and reasons for this are needed.

5. Mixture Analysis Tests

Besides bleeding and poor skid resistance, an additional problem with some in-place SMA mixtures is that they have ravelled or aggregates have popped out of the surface. Although causes have not been thoroughly documented in reports that are available, the author recommends that tests for moisture susceptibility be performed. Ravelling may be due to moisture damage, inadequate coating due to poor mixing, and/or to poor compaction. Inadequate coating due to an insufficient amount of binder can also lead to ravelling in dense-graded mixtures. However, SMA mixtures have thicker coatings and thus should have sufficient binder even if the binder content is slightly less than optimal. The minimum binder contents recommended by the author in the previous section should provide thick coatings and also reduce the effects of water.

Recommended test methods to estimate moisture susceptibility are ASTM D 4867, entitled "Effect of Moisture on Asphalt Concrete Paving Mixtures," and AASHTO T 283, entitled "Resistance of Compacted Bituminous Mixture to Moisture Induced Damage."[1,3] These are commonly called the Root-Tunnicliff and Lottman tests, respectively. Tests for moisture susceptibility may have to be modified for SMA mixtures. For example, it is not known whether air void levels of 6 to 8 percent, which are used in some tests for moisture susceptibility, are applicable to SMA mixtures. SMA mixtures should compact when being rolled in the field to air void levels below 6 percent, and therefore, lower air void levels may be more appropriate. However, high air void levels are often needed in a laboratory test to accelerate the damage that can occur in pavements over their lives. Until more is learned about SMA mixtures, the author recommends that a level of 5 to 6 percent be used. These air void levels are obtained by reducing the compactive effort.

Structural tests such as repeated load and creep tests generally have not been performed on SMA mixtures in Sweden or Germany, and little laboratory data is available which compare SMA mixtures to dense-graded mixtures. There are also few experimentally designed field comparisons between SMA mixtures and dense-graded mixtures. There seem to be few written reports regarding which of these two mixtures perform better when good quality materials are used in both. However, the Europeans verbally report that SMA surfaces show little to no permanent deformations and they expect them to last, on an average, between 20 to 40 percent longer than dense-graded mixtures. Although the majority of SMA pavements are less than 8 years old because the use of these mixtures has been expanding, some SMA pavement surfaces are more than 14 years old. In the past, SMA technology was mainly developed by paving contractors and highway officials through field experiences and trial pavement sections.

Currently there is research being performed in Germany and the Netherlands on the resistance of SMA mixtures to permanent deformation using creep, repeated load, and wheel-tracking tests. The resistance to cracking is being determined using a three point bending beam test and wheel-tracking tests. The three point bending beam test is performed at temperatures of 32, 14, and 5 °F (0, -10 and -15 °C) until the beam fails. The Germans relate the deflections at failure to the ability of the mixture to resist flexural fatigue. Greater deflection means increased fatigue resistance. Most SMA mixtures have been placed on stable binder and base layers. However, as the use of this type of mixture expands to pavements with greater deflections, it is desirable to know how they will perform under these conditions.

The Swedes are also starting to perform repeated load and tensile tests on SMA mixtures. Preliminary data indicate that the diametral moduli and indirect tensile strengths of SMA mixtures are lower than comparable dense-graded mixtures. This may be due to the thick binder films. Whether this testing configuration is applicable to SMA mixtures needs to be determined.

CHAPTER 2: GEORGIA SMA PROJECT

The Georgia Department of Transportation (GDOT) placed SMA experimental pavement sections on Interstate 85, north of Route 53, Jackson County, GA. This site is northeast of Atlanta, GA. Both binder and surface SMA layers were placed in the southbound, driving lanes. Aggregates from two sources were used in the 1.5-in (38-mm) surface layer while one was used in the 2.25-in (57-mm) binder layer. The binder layer was placed on July 31, 1991 and the surface layers were placed on September 4, 17, and 18. Dense-graded control sections and open-graded mixtures were also placed as part of this experimental project.

A portion of this experimental project was funded under FHWA Test and Evaluation Project No. 18 (TE-18). This project is administered by the Roadway Applications Branch (HTA-21), which is in the Engineering Applications Division of the Office of Technology Applications. The goal of TE-18 is to evaluate and implement European SMA technology in the U.S. It is a cooperative effort between the FHWA, State highway agencies, and industry. TE-18 was started in response to the recommendations from the 1990 European Asphalt Study Tour (EAST).(6)

The mixture designs presented in this chapter were performed to assist GDOT in determining an optimal asphalt content and evaluating the mixtures. This work was performed in the Bituminous Mixtures Laboratory located at the Turner-Fairbank Highway Research Center (TFHRC) in McLean VA. This laboratory is part of the Pavements Division (HNR-20) of the Office of Engineering and Highway Operations Research and Development. GDOT performed their own mixture designs and also had other organizations perform designs. The binder contents chosen by GDOT were based on all of this mixture design work. Therefore, the binder contents presented in this report do not exactly match the contents used in the pavement sections. All work for this Georgia SMA project will be summarized under TE-18.

All asphalt, aggregate, and mixture design tests and procedures performed in the TFHRC laboratory were according to AASHTO and recommended practices.(3,7)

1. Aggregate Properties

The primary aggregates used in the mixtures were from the Ruby granite quarry in GA, owned by Martin Marietta, and from the Buford granite quarry in GA, owned by Blue Circle. Both aggregates were used in the surface layer. The Buford aggregate was also used in the binder layer. During this project, GDOT developed two SMA specifications, one for a fine SMA mixture and one for a coarse SMA mixture. Both surface mixtures were classified under the fine SMA specification, while the binder mixture was classified under the coarse SMA specification.

The as-received washed gradations, specific gravities, water absorptions, and Los Angeles (L.A.) abrasions for the Rudy and Buford aggregates are given in table 2. These aggregates were 100 percent crushed. The Ruby aggregate had a low L.A. abrasion of 20.0, while the Buford aggregate had a moderately high L.A. abrasion of 36.4. Both were below the maximum abrasion loss of 40 percent by weight recommended for aggregates used in open-graded mixtures. Each aggregate was sieved into each size down to the #8 sieve.

Properties for the mineral filler and hydrated lime used in the mixtures are also given in table 2. One-percent hydrated lime was added as an antistripping agent. Mineral filler was added to increase the total minus #200 sieve material to 10 percent by aggregate weight. As shown in table 2, three mineral fillers were received, but based on initial mixture design work performed by GDOT, it was decided to use the RO-4 mineral filler. The two other mineral fillers were eliminated. All three mineral fillers were obtained by crushing the same marble aggregate from the quarry at Marble Hill in GA, owned by Georgia Marble.

Only the apparent specific gravities for the filler and the lime could be measured. These apparent specific gravities were used in place of the bulk dry and bulk saturated surface dry specific gravities when calculating the combined specific gravities for the aggregate blends used in the mixtures. It was assumed that the water absorptions of the fillers and the lime were zero. This assumption could be made without adversely affecting the data because these materials made up less than 14 percent of the aggregate and the absorptions of the other aggregates were low. This is also the typical practice.

Tables 3 through 5 show the gradations of the aggregates used in the three mixtures. GDOT changed two of the aggregate gradations in table 2 after the aggregates were received at TFHRC. These changes had been made in the GDOT laboratory and in the stockpiled aggregates at the hot-mix plant so that the overall target gradations could be obtained. There were also some minor discrepancies between the as-received gradations in table 2 and the reported gradations of the stockpiled aggregates. Therefore, it was decided to adjust the gradations of the aggregates used in this study so that they were more representative of the gradations at the plant. Because the aggregates had been sieved down to the #8 sieve, the gradations above this size were made to exactly match the gradations of the aggregates at the plant. Below this size the differences between the gradations were minor. The blend percentages used in the three mixtures are also given in tables 3 through 5.

The percent total flat and elongated particles for the combined plus #4 aggregates using the length to thickness test are given in table 6. Both 3 to 1 and 5 to 1 length to thickness tests were used. GDOT currently uses a length to thickness test, which is in agreement with the German method discussed in chapter 1. The percentages were calculated on both a weight and a number of particles basis. The aggregates passed the GDOT specification which allows a maximum of 10 percent aggregate by weight greater than a 5 to 1 length to thickness. This is a very lenient specification, and the author expects that few aggregates would fail it. It is recommended that in future SMA studies, the German limit of 20 percent by weight using the 3 to 1 length to thickness test be used for SMA aggregates. All three aggregates failed this specification.

The calculated gradations for the three aggregate blends and the target gradations are given in tables 7 through 9. The gradations of the blends are also shown in figures 8 and 9. These gradations were very close to the targets. GDOT developed the target gradations and the specifications in these tables.

Table 2. As-received washed gradations of the Georgia aggregates.

Sieve Size	Martin Marietta Granite at Ruby Quarry, GA, B-6029 Percent Passing For Each Aggregate Classification #6	#7	#89	W-10
1 in	100.0			
3/4 in	77.5	100.0		
1/2 in	8.6	94.1	100.0	
3/8 in	2.8	43.5	98.3	100.0
#4	2.0	1.4	13.9	98.1
#8	1.9	0.6	1.7	75.0
#16	1.7	0.5	0.8	50.2
#30	1.5	0.4	0.6	33.5
#50	1.4	0.3	0.5	21.3
#100	1.3	0.3	0.4	11.1
#200	1.2	0.2	0.3	5.3
BSG (DRY)	2.741	2.730	2.735	2.682
BSG (SSD)	2.751	2.741	2.746	2.701
APP SG	2.769	2.761	2.767	2.736
Abs, %	0.36	0.42	0.43	0.74

L.A. Abrasion of coarse aggregate (Grading B of AASHTO T 96) = 20.0

(in)(2.54)=(cm)

Note 1: "B" numbers in the tables are FHWA identification numbers.

Table 2. As-received washed gradations of the Georgia aggregates (continued).

Blue Circle Granite at Buford Quarry, GA, B-6028

Sieve Size	Percent Passing For Each Aggregate Classification #6	#7	#89	W-10
1 in	100.0			
3/4 in	96.8	100.0		
1/2 in	16.7	91.1	100.0	
3/8 in	2.4	27.2	98.0	100.0
#4	1.0	1.9	28.1	98.6
#8	0.9	1.6	8.1	79.5
#16	0.8	1.3	5.1	52.0
#30	0.7	1.1	3.9	36.4
#50	0.6	0.9	3.2	24.0
#100	0.5	0.7	2.3	9.1
#200	0.4	0.6	1.4	2.9
BSG (DRY)	2.652	2.656	2.644	2.632
BSG (SSD)	2.662	2.666	2.655	2.642
APP SG	2.678	2.685	2.674	2.658
Abs, %	0.36	0.40	0.42	0.38

L.A. Abrasion of coarse aggregate (Grading B of AASHTO T 96) = 36.4

(in)(2.54)=(cm)

Table 2. As-received washed gradations of the Georgia aggregates (continued).

	Percent Passing For Each Aggregate Classification			
	Mineral Fillers			
Sieve Size	Marblend B-6030	RO-4 B-6031	9CS B-6032	Hydrated Lime B-6035
#4				
#8				
#16				
#30	100.0	100.0		100.0
#50	90.2	99.6	100.0	99.1
#100	63.3	95.8	99.8	98.5
#200	50.2	71.2	99.0	95.4
APP SG	-	2.731	-	2.345

Note 1: The mineral fillers were obtained by crushing marble aggregate from the Marble Hill quarry in GA.

Note 2: The hydrated lime used in the mixture designs was from Blue Circle Inc., Birmingham, AL. However, the lime used in the pavement mixture was from Luttrell, TN. Contractors can choose lime from different sources.

Note 3: It was assumed that the water absorptions of the fillers and hydrated lime were zero. The apparent specific gravities were used in all calculations.

Table 3. Washed gradations for the Ruby fine SMA aggregates.

Sieve Size	Percent Passing For Each Aggregate Classification #7	#89	W-10	RO-4	Hydrated Lime
1 in					
3/4 in					
1/2 in	100.0	100.0			
3/8 in	48.0	99.0	100.0		
#4	4.0	25.0	98.0		
#8	1.0	3.0	73.0		
#16	0.9	1.4	48.9		
#30	0.8	1.1	32.6	100.0	100.0
#50	0.7	0.9	20.7	99.6	99.1
#100	0.7	0.7	10.8	95.8	98.5
#200	0.6	0.5	5.2	71.2	95.4
Blend, %	34	39	15	11	1

(in)(2.54)=(cm)

Table 4. Washed gradations for the Buford fine SMA aggregates.

Sieve Size	Percent Passing For Each Aggregate Classification				
	#7	#89	W-10	RO-4	Hydrated Lime
1 in					
3/4 in					
1/2 in	100.0				
3/8 in	53.0	100.0	100.0		
#4	2.0	43.0	97.0		
#8	1.0	22.0	76.0		
#16	0.8	13.9	49.7		
#30	0.7	10.6	34.8	100.0	100.0
#50	0.6	8.7	22.9	99.6	99.1
#100	0.4	6.2	8.7	95.8	98.5
#200	0.4	3.8	2.8	71.2	95.4
Blend, %	44	40	5	10	1

(in)(2.54)=(cm)

Table 5. Washed gradations for the Buford coarse SMA aggregates.

Sieve Size	Percent Passing For Each Aggregate Classification #6	#7	#89	W-10	RO-4	Hydrated Lime
1 in						
3/4 in	100.0	100.0				
1/2 in	29.0	90.0				
3/8 in	7.0	48.0	100.0	100.0		
#4	2.0	2.0	43.0	97.0		
#8	2.0	1.0	22.0	76.0		
#16	1.8	0.8	13.9	49.7		
#30	1.6	0.7	10.6	34.8	100.0	100.0
#50	1.3	0.6	8.7	22.9	99.6	99.1
#100	1.1	0.4	6.2	8.7	95.8	98.5
#200	0.9	0.4	3.8	2.8	71.2	95.4
Blend, %	55	11	17	4	12	1

(in)(2.54)=(cm)

Table 6. Percent flat and elongated particles in the Georgia coarse aggregates.

		Percent Flat and Elongated Particles	
Aggregate type	Length to Thickness	by weight	by number
Ruby Quarry			
Fine SMA Gradation	3 to 1	29.9	34.2
	5 to 1	7.6	10.2
Buford Quarry			
Fine SMA Gradation	3 to 1	36.7	40.3
	5 to 1	5.0	8.0
Buford Quarry			
Coarse SMA Gradation	3 to 1	29.5	33.8
	5 to 1	4.7	7.3

Note: The GDOT specification allows a maximum of 10.0 percent by weight using the 5 to 1 length to thickness test.

Table 7. Gradations for the Ruby fine SMA mixture design.

BLEND	
Aggregate	Percent
# 7	34
# 89	39
W-10	15
RO-4	11
Hydrated Lime	1

	Percent Passing			
Sieve Size	FHWA Method	GDOT Method	GDOT Target	GDOT Specification Limits
3/4 in				
1/2 in	100.0	100.0	100	100
3/8 in	81.9	81.9	81	70 - 90
#4	37.8	37.8	37	28 - 50
#8	24.5	24.5	23	20 - 26
#16	20.2	19.3	19	
#30	17.6	16.9	16	
#50	15.6	15.1	14	10 - 20
#100	13.7	13.2	12	
#200	10.0	9.6	10	8 - 13

BSG (DRY)	2.718
BSG (SSD)	2.729
APP SG	2.749
Abs, %	0.42

(in)(2.54)=(cm)

Table 8. Gradations for the Buford fine SMA mixture design.

BLEND

Aggregate	Percent
# 7	44
# 89	40
W-10	5
RO-4	10
Hydrated Lime	1

Sieve Size	Percent Passing FHWA Method	GDOT Method	GDOT Target	GDOT Specification Limits
3/4 in				
1/2 in	100.0	100.0	100	100
3/8 in	79.3	79.3	78	70 - 90
#4	33.9	33.9	36	28 - 50
#8	24.0	24.0	23	20 - 26
#16	19.4	19.0	18	
#30	17.3	17.0	17	
#50	15.8	15.6	15	10 - 20
#100	13.7	13.5	13	
#200	9.9	9.8	10	8 - 13

BSG (DRY)	2.652
BSG (SSD)	2.661
APP SG	2.678
Abs, %	0.36

(in)(2.54)=(cm)

Table 9. Gradations for the Buford coarse SMA mixture design.

BLEND

Aggregate	Percent
# 6	55
# 7	11
# 89	17
W-10	4
RO-4	12
Hydrated Lime	1

	Percent Passing			
Sieve Size	FHWA Method	GDOT Method	GDOT Target	GDOT Specification Limits
3/4 in	100.0	100.0	100	100
1/2 in	59.9	59.9	62	50 - 75
3/8 in	43.1	43.1	42	35 - 50
#4	25.5	25.5	26	
#8	21.0	21.0	20	18 - 22
#16	18.4	17.4	16	
#30	17.2	16.2	15	
#50	16.1	15.3	14	10 - 20
#100	14.5	13.9	12	
#200	10.8	10.3	10	8 - 13

BSG (DRY)	2.654
BSG (SSD)	2.662
APP SG	2.677
Abs, %	0.33

(in)(2.54)=(cm)

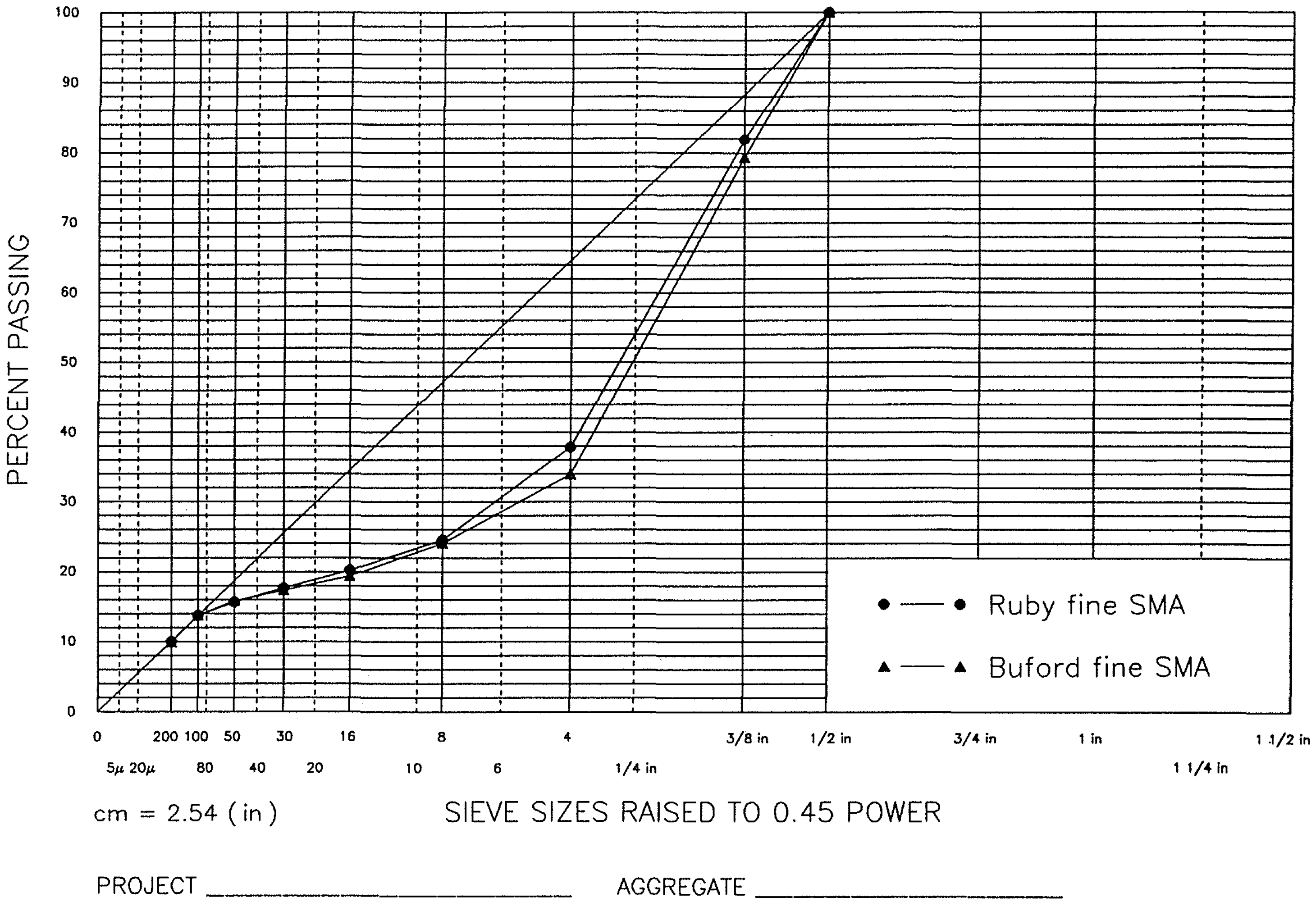


Figure 8. Gradations for the Ruby and Buford fine SMA mixture designs.

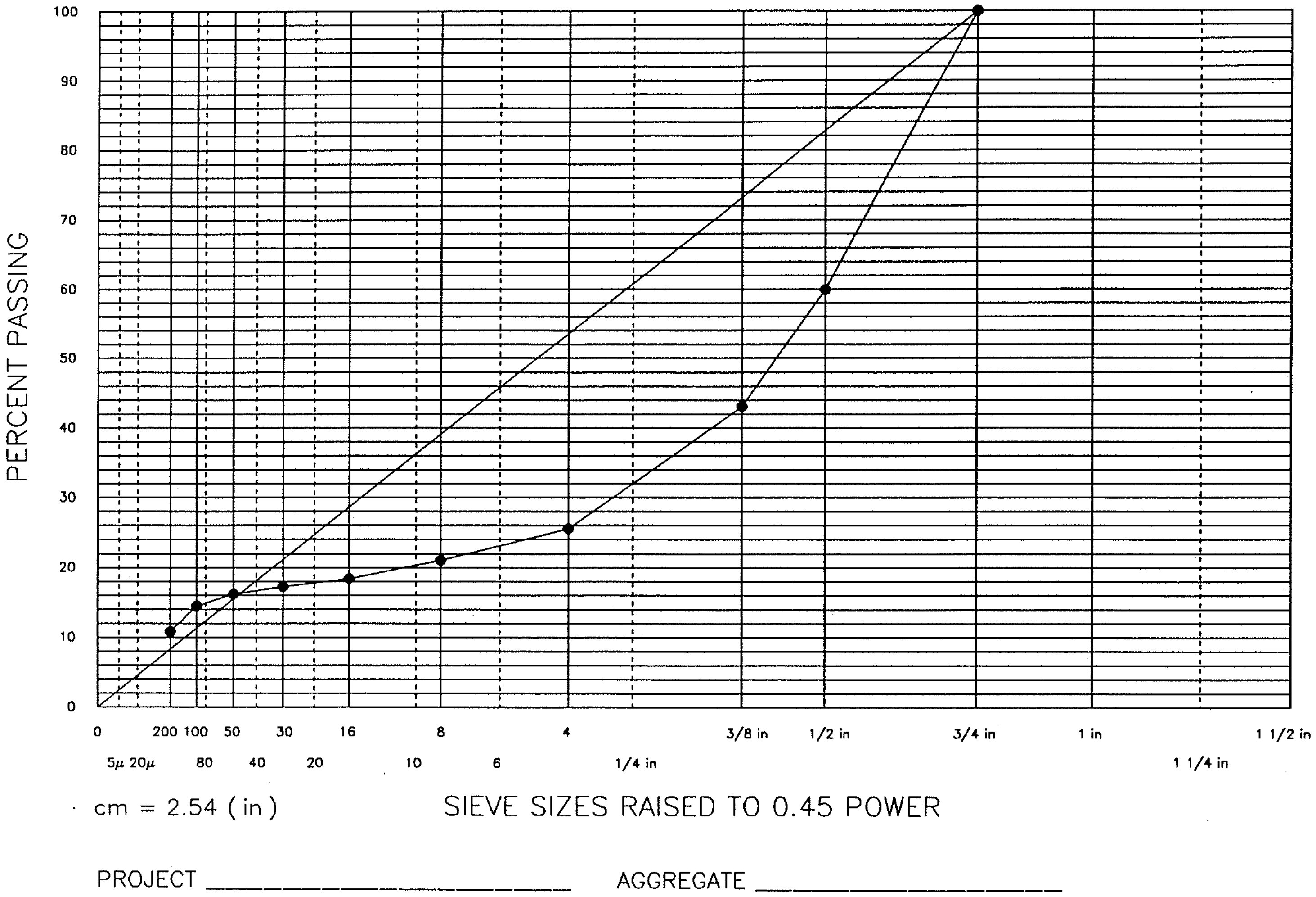


Figure 9. Gradation for the Buford coarse SMA mixture design.

Two methods of calculating the gradations were used. The FHWA method of calculating the gradations was based on washed sieve analyses of all materials above the #200 sieve. Figures 8 and 9 are the gradations using this method. Gradations using the GDOT method are included for additional information. GDOT does not perform washed sieve analyses on coarse aggregates which have very little material passing the #8 sieve, such as the #6 and #7 aggregates used in this study. Also, GDOT assumed that the hydrated lime was 100 percent passing the #200 sieve. Normally only 2 to 5 percent of a hydrated lime is retained on the #200 sieve. These are common practices used by many highway agencies.

2. Binder Properties

The properties of the AC-30 Novophalt-modified binder used in the mixtures are given in table 10. In the Novophalt process, a linear low density polyethylene is dispersed into an asphalt. The binder had an absolute viscosity of 9,131 Poise (913.1 Pa-sec) at 140 °F (60 °C). The low solubility level of 94.80 percent in trichloroethylene reflects the insolubility of the 5.0 percent polyethylene.

The Novophalt process was used to reduce the temperature susceptibility of the binder, primarily by increasing the stiffness at high temperatures. The polyethylene should also act, as least partially, as a stabilizing additive to prevent drainage and bleeding, but a fiber was chosen by GDOT to be the primary stabilizer. GDOT indicated that a fiber was needed to obtain their required binder contents and to prevent drainage. The modified binder alone was not sufficient. GDOT has used the Novophalt process in dense-graded mixtures and chose to use it in this project.

The properties of the Novophalt-modified binder used in the pavement sections may be slightly different from the properties in table 10. The Novophalt-modified binder used in the pavement sections was made at the hot-mix plant at the time of construction. There may also be some variations in the properties of the pavement binder depending on which day the binder was produced.

3. Stabilizing Additive

GDOT used a rock wool fiber from Sweden called InorPhil^{TM} 063-60. The source of this fiber is given in table 11. This product is manufactured from diabase rocks with some limestone at 2910 °F (1600 °C). The fibers are very short at 0.008 to 0.08 in (0.2 to 2 mm). The average thickness and aspect ratio are 0.00016 in (4 um) and 0.0036, respectively. The fibers are generally considered part of the aggregate in the mixture. Bags containing the fibers are added to the aggregate in the hot-mix plant pugmill by manual labor. The bags melt and become part of the mixture. InorPhil is delivered in polyethylene bags, each containing 31.2 lb (14.2 kg) of material.

A Swedish construction company named Skanska, which uses InorPhil, suggested that GDOT incorporate a minimum of 8 percent fiber by binder weight. GDOT considered the fibers to be part of the aggregate. Basing the percentage of fibers on the binder weight is not practical for mix design purposes when the fiber is considered aggregate. As the binder content is varied, both the fiber weight and the aggregate batch weights must be varied by insignificant

Table 10. Properties of the AC-30 Novophalt-modified binder.

Physical Properties	Virgin Novophalt-Modified Binder	TFOT
Thin Film Oven Test, percent loss		0.21
Penetration, 25 °C (100 g, 5 s), 0.1 mm	49	36
Kinematic Viscosity, 135 °C, cSt	1759	2571
Absolute Viscosity, 60 °C, P	9131	22752
Specific Gravity, 25/25 °C	1.026	
Water, percent	0	
Flash Point, COC, °C	277	
Solubility in Trichloroethylene, percent	94.80	

Source of AC-30 Asphalt Binder, B-6034:

Amoco AC-30 at the Doraville Facility
Gwinnett County, GA

(Modified with 5.0 percent polyethylene (Novophalt process) at the hot-mix plant.)

(°F - 32)/1.8 = °C   (P)(0.1) = Pa-sec   (cSt)(1E-06) = m^2/s

Table 11. Source of the rock wool fiber.

Name: InorPhil^{TM} 063-60 Mineral Fiber
Quantity Used: 0.51 percent by aggregate weight

(The apparent specific gravity was assumed to be 2.3 and the water absorption was assumed to be zero)

Laxa Bruks AB
Rofors
S-695 00 Laxa
Sweden

Fiberand Corporation
7150 Southwest 62nd Avenue
South Miami, FL 33143
(305) 661-4506

amounts. To circumvent this problem, an optimal binder content of 6 percent was assumed prior to the design. The fibers were added as 0.08 x 6 percent which is 0.48 percent by mix weight and 0.51 percent by aggregate weight. Therefore, 0.51 percent fiber by aggregate weight was used in all mixtures, and the weights of the aggregate and the fiber were both constant at each binder content used in the design.

Three other materials were also considered in this study. Each of these are also added to the aggregate. One was a gray, loose cellulose fiber called Arbocel™ ZZ 8/1. This fiber is manufactured in Germany by J. Rettenmaier & Sohne GmbH+Co and is distributed in North America by ScanRoad, Waco, TX, at (817) 772-7677 or (800) 283-7226. The maximum length of this fiber is 0.2 in (5 mm) and an average length is 0.043 in (1.1 mm). The average thickness and aspect ratio are 0.0018 in (45 um) and 0.041, respectively. These fibers are longer, thicker, and have an average aspect ratio which is 11 times higher than the InorPhil rock wool fibers. Like the InorPhil fibers, these cellulose fibers are added to the pugmill in polyethylene bags by manual labor. Arbocel ZZ 8/1 is delivered in polyethylene bags, each containing 2.2 lb (1 kg) of material, but larger bags are available upon request.

The third material was called Arbocel™ Bitumen Granulate 50/50 (Arbocel BG 50/50), also called Viatop™. Arbocel BG 50/50 consists of the same cellulose fiber in Arbocel ZZ 8/1 which has been pelletized by mixing it with 25 penetration grade asphalt. In the past, 40 to 50 penetration grade asphalt has also been used. The fiber is pelletized so that either a manual or an automatic method of adding fiber to an aggregate at a hot-mix plant can be used. The pellets are from 0.5 in (13 mm) to less than 0.1 in (2.5 mm) in length and have a diameter of 0.16 in (4 mm). Arbocel BG 50/50 is 50 percent asphalt and 50 percent fiber by total weight. Thus, twice as much Arbocel BG 50/50 by weight is added to the aggregate compared to Arbocel ZZ 8/1. The weight of the asphalt in the pellets is added to the weights of the asphalt used in a mixture design to determine the total binder content. Arbocel BG 50/50 is delivered in 2200 lb (1000 kg) bags.

The fourth material was Vestoplast™-S. Vestoplast-S is a ethylene-propylene-butylene-terpolymer which is doubled-bond free with no other functional groups. It is manufactured in Germany by the Huls Chemical Company and is distributed in the U.S. by ATC Company, Richmond, IN, at (317) 935-1750. Vestoplast-S is obtained in pellet form, each pellet being 0.125-in (3.2-mm) in length by 0.125-in (3.2-mm) in diameter. The pellets are transported in plastic bags, each containing 44 lb (20 kg) of material.

Vestoplast-S pellets soften between 176 and 311 °F (80 and 155 °C) and typically close to 220 °F (104 °C). The specific gravity is approximately 0.86. The supplier reports that this material increases the adhesion between the aggregate and asphalt and decreases the temperature susceptibility of the binder, mainly by increasing the stiffness of the binder at high temperatures. This stabilizer is used to both stabilize and modify SMA binders. It has also been used to modify binders for dense-graded mixtures. It has never been used in combination with Novophalt polyethylene-modified binders.

The supplier recommends that in the laboratory, Vestoplast-S be added to the hot aggregate and dry mixed for 10 to 20 sec. During this time the pellets will melt and become blended. Even though it is added to the aggregate, the dosage rate is typically 7 percent by weight of the binder, and the polymer is considered a part of the binder. The supplier also recommends that normal mixing and compaction temperatures be used in the laboratory. The effects of this additive on binder properties such as viscosity are unknown, although the absolute viscosity of a binder at 140 °F (60 °C) typically increases by a factor of 2 to 4.

4. Mixing Studies

Laboratory mixing studies were performed at TFHRC using all four stabilizers, even though it was decided by GDOT to use the InorPhil fiber in their SMA mixtures. How the Arbocel BG 50/50 pellets would breakdown was a major concern. Visually, all four stabilizers mixed with the aggregate and asphalt quite readily by the normal mixing time of 1 minute. However, it is difficult to determine a degree of distribution when all materials are coated black. When the mixing time was cut in half to 30 sec, some portions of the Arbocel BG 50/50 pellets were found in the mixture. Only the Buford fine SMA materials were used in these mixing studies, and the laboratory mixing temperature was 325 °F (163 °C) in all cases.

These results, especially when using Arbocel BG 50/50 pellets, may not be applicable for lower mixing temperatures. The mixing study simply showed that all of the stabilizers can be mixed, at least on a visual basis, with the asphalt and aggregate. Also, the mixing time of 1 minute is a standard practice used in the TFHRC laboratory. This does not mean the wet mixing times for the four stabilizers at a hot-mix plant will be equivalent. This must be determined at the plant. The mixing action in the laboratory does not duplicate the action at a hot-mix plant.

5. Mixture Design

For the three SMA mixture designs using the InorPhil fiber, the samples of fiber for each aggregate batch were broken apart and added to the aggregate prior to heating. The laboratory mixing temperature was 325 °F (163 °C) and the compaction temperature was 310 to 315 °F (154 to 157 °C). These temperatures were based on past experiences of GDOT using Novophalt-modified binders, although, in these past experiences, the mixtures did not contain fibers or the high minus #200 dust contents used in SMA mixtures. These could further stiffen the binder. There was no firm basis for choosing mixing and compaction temperatures in this project.

Based on the Novophalt-modified binder viscosities shown in table 10 and the viscosity requirements given in the Marshall method of AASHTO T 245, entitled "Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus," the mixing and compaction temperatures should be approximately 365 and 345 °F (185 and 174 °C), respectively.[1,3] Temperatures this high are generally not used with the Novophalt process, and there is a general perception in the hot-mix industry that the viscosity-temperature relationship used by the Marshall method is not applicable to many modified binders. Optimal binder contents are often obtained using lower mixing and compaction temperatures, but there is no standard way of determining these temperatures.

Mixture design information is given in tables 12 through 14. A 50-blow Marshall design was used. The optimum binder content was taken at a 3.5

percent air void level. GDOT requested that the design be based on this air void level, and the Marshall stabilities, Marshall flows, and the voids filled with asphalt cement (VF) be adequate at this level. This air void level is the midpoint of the their specification for SMA mixtures, which requires a 3 to 4 percent design air void level. GDOT also required a binder content between 5.5 and 7.5 percent by mixture weight, a minimum stability of 1500 lbf (6672 N), a flow between 5 and 16, and VF between 65 and 85.

Extra effort was needed by the technicians to break the loose mixtures apart when determining their maximum specific gravities in accordance with AASHTO T 209, entitled "Maximum Specific Gravity of Bituminous Paving Mixture."(3) This indicated that the mixtures were stiff. The loose mixtures and compacted specimens were dull in appearance because of the fibers. (The loose mixtures evaluated in the mixing studies which contained cellulose fibers or Vestoplast-S polymer were not as dull. The Vestoplast-S mixtures were shiny.)

The optimal binder contents for the Ruby fine SMA, Buford fine SMA, and Buford coarse SMA, were 5.75, 5.55 and 5.65 percents by mixture weight, respectively. These contents are in the range specified by GDOT, but are lower than those generally used in Europe. However, most mixture designs in Sweden and Germany are based on a 3-percent air void level. At a 3-percent air void level, the binder contents of the three mixtures would be close to the recommended level of 6 percent given in chapter 1. Marshall stabilities, flows, VMA, and VF were acceptable according to GDOT and other standards for dense-graded mixtures.(7) The results of these designs were reported to GDOT for their use. The author recommends that in future studies, higher binder contents be used as in European practices.

The German drainage test given in appendix A was performed on the Buford coarse mixture. The only modification was that GDOT's mixing temperature of 325 °F (163 °C) was used instead of the 275 °F (135 °C) temperature given in the method. The weight loss was only 0.05 percent, which indicates that drainage should not be a problem. Less than a 0.3 percent loss is required. The drainage test was not performed on the two fine SMA mixtures, but these mixtures appeared even less fluid when hot than the coarse mixture. This test was developed for cellulose fibers, but no reason could be found for not accepting the test result.

One-percent hydrated lime by aggregate weight was included in the mixtures as an antistripping agent. This is a standard practice used by GDOT when using these aggregates. Tests for moisture susceptibility were not performed at TFHRC but were performed by GDOT. All three mixtures passed the GDOT test, which is based on AASHTO T 283.(3)

Table 12. Mixture design properties for the Ruby fine SMA gradation.

						Optimal
Binder Content, % by mix wt	5.0	5.5	6.0	6.5	7.0	5.75
Maximum Specific Gravity	2.527	2.508	2.489	2.470	2.452	2.498
Density, lbf/ft^3	148.4	149.9	150.4	150.4	149.7	150.3
Marshall Stability, lbf	2970	2810	2740	2660	2380	2780
Marshall Flow, 0.01 in	12.0	13.0	12.0	14.3	12.5	12.5
Air Voids, %	5.9	4.2	3.2	2.4	2.1	3.5
VMA, %	16.9	16.5	16.6	17.0	17.9	16.5
VFA, %	65.2	74.3	81.0	85.7	88.1	77.5

Marshall Design Blows = 50
Mixing Temperature = 325 °F (163 °C)
Compaction Temperature = 310 °F (154 °C)

Effective SG Aggregate = 2.738

(in)(2.54)=(cm) (lbf)(4.448) = (N) (lbm/ft^3)(16.01) = Kg/m^3

Table 13. Mixture design properties for the Buford fine SMA gradation.

						Optimal
Binder Content, % by mix wt	5.0	5.5	6.0	6.5	7.0	5.55
Maximum Specific Gravity	2.465	2.447	2.429	2.411	2.394	2.445
Density, lbf/ft^3	146.2	146.9	147.1	146.8	146.4	147.0
Marshall Stability, lbf	3420	3260	2980	2530	2380	3200
Marshall Flow, 0.01 in	12.3	12.2	11.8	12.2	13.7	12.1
Air Voids, %	5.0	3.8	2.9	2.4	2.0	3.5
VMA, %	16.1	16.1	16.4	17.1	17.7	16.2
VFA, %	69.2	76.4	82.2	85.8	88.7	77.5

Marshall Design Blows = 50
Mixing Temperature = 325 °F (163 °C)
Compaction Temperature = 310 °F (154 °C)

Effective SG Aggregate = 2.661

(in)(2.54)=(cm) (lbf)(4.448) = (N) (lbm/ft^3)(16.01) = Kg/m^3

Table 14. Mixture design properties for the Buford coarse SMA gradation.

						Optimal
Binder Content, % by mix wt	5.0	5.5	6.0	6.5	7.0	5.65
Maximum Specific Gravity	2.465	2.447	2.429	2.411	2.394	2.441
Density, lbf/ft^3	146.7	146.7	147.0	146.5	146.0	146.8
Marshall Stability, lbf	2960	2690	2410	2390	2320	2580
Marshall Flow, 0.01 in	10.5	12.2	10.3	12.0	18.8	11.3
Air Voids, %	4.6	3.9	3.0	2.6	2.3	3.5
VMA, %	15.9	16.3	16.6	17.3	18.0	16.4
VFA, %	70.7	76.1	81.6	84.8	87.3	78.2

Marshall Design Blows = 50
Mixing Temperature = 325 °F (163 °C)
Compaction Temperature = 310 °F (154 °C)

Effective SG Aggregate = 2.661

(in)(2.54)=(cm) (lbf)(4.448) = (N) (lbm/ft^3)(16.01) = Kg/m^3

CHAPTER 3: RECOMMENDATIONS

- A set of master grading limits proposed by the author is given in table 1 of chapter 1. If these limits are used, the SMA gradation will meet either Swedish or German SMA specifications.

- Until more is learned about SMA gradations and mixtures, the author recommends that an SMA JMF gradation and its tolerances fit as closely as possible inside the master grading band envelope, such as the ones given in table 1. This recommendation is intended to reduce the number of possible gradations that can be used in initial SMA projects in the U.S.

- The author recommends that when a band from table 1 is used, the JMF gradation be near the low end of the band at the #8 sieve (or the #10 sieve if this size is used). Most gradations must be as open or gap-graded as possible in order to meet minimum binder content requirements.

- Studies should be performed to determine whether JMF gradation tolerances for dense-graded mixtures are applicable to SMA mixtures. The effects of variations on the #8 and #200 sieves are most important.

- Data is needed to determine the importance of the gradation of the minus #200 dust and its effects on extending the binder. More information is needed on the properties of the minus #200 materials used in Europe. (The gradation of the dust was not determined in the work performed for GDOT given in chapter 2. It should be determined in all future studies.)

- Little is known about the effects of rounded aggregate surfaces on the performances of SMA mixtures. Therefore, the author recommends that the German specification for crushed particles be used. This specification is interpreted as requiring that the coarse aggregate have at least 90 percent particles with two or more mechanically induced fractured faces. Each size fraction above the #4 sieve should be tested. An overall value for the coarse aggregate should be determined based on the proportions of the various coarse aggregate sizes used in the JMF.

- Little is known about the effects of elongated and flat pieces on the performances of SMA mixtures. Therefore, the author recommends that the German test and specification for flat and elongated particles be used. This specification requires the coarse aggregate to have maximum of 20 percent aggregate by weight passing a 3 to 1 length to thickness test. Each size fraction above the #4 sieve should be tested. An overall value for the coarse aggregate should be determined based on the proportions of the various coarse aggregate sizes used in the JMF.

- SMA aggregate quality specifications should be at least as strict as those for open-graded mixtures.

- Most aggregates used in Sweden and Germany have low water and binder absorptions, generally below 2 percent. Whether highly absorptive aggregates can be used in SMA mixtures is unknown and needs to be determined.

- There is no apparent reason why highway agencies in the U.S. cannot use their normal grade of binder in SMA mixtures.

- To duplicate European practice, the author recommends that the binder content be a minimum of 6.3 percent by mixture weight at a 3-percent design air void level when absorptive cellulose fibers are used and 6.0 percent for other stabilizers. Stabilizers other than cellulose generally do not absorb and hold as much binder. Thus it is generally easier with cellulose fibers to increase the gap in the gradation to obtain more VMA and higher binder contents without drainage.

- The previously recommended minimum binder contents are based on using a 50-blow per side Marshall hammer compaction.

- The previously recommended minimum binder contents may be difficult to obtain when the aggregate gradation has more than 10 percent material by weight retained on the 3/4-in (19-mm) sieve. Data on large aggregate mixtures is insufficient to make firm recommendations for them.

- The previously recommended minimum binder contents may be difficult to obtain if mineral fillers used in the U.S. have more material smaller than 0.00079 in (20 um) compared to European mineral fillers. This is unknown.

- The previously recommended minimum binder contents may be difficult to obtain when the aggregate has a high specific gravity. Minimum binder contents should be based on volume relationships. When based on weight, mixtures with aggregates having high specific gravities are required to have more binder by volume. Current German specifications allow some reduction in binder content when the apparent specific gravity of the aggregate is greater than 2.8.

- The previously recommended minimum binder contents will be easier to obtain as the absorption of the aggregate increases. Therefore, minimum binder contents should be based on the effective binder content. They are currently not based on the effective binder content.

- For a fixed gradation and air void content, different stabilizers can provide different binder contents. These differences are not related to differences in the volumes of the stabilizers or whether they are considered binder or aggregate. Cellulose fibers provide the highest binder contents and this is another reason why minimum binder contents are easier to obtain using them. Reasons for these differences are unknown and need to be determined.

- The differences in binder contents for a fixed gradation and air void content due to the stabilizers may mean that they affect how a mixture compacts. If so, the mixture design process is confounded. Minimum binder contents for one stabilizer, such as for cellulose fibers, may not be applicable to other stabilizers. Also, the higher binder contents provided by cellulose fibers may mean slightly less stone-on-stone contact in some cases.

- Mechanical tests which predict rutting susceptibility are needed for SMA mixtures to determine whether the chosen SMA mixture will provide the desired properties. Mechanical tests would eliminate the process of trying to obtain high coarse aggregate stone-on-stone contact by means of minimum binder contents. They would also eliminate the confounding mixture design problems caused by the different stabilizers.

- A drainage test applicable to all stabilizers is needed. Drainage tests are used to determine if the binder and aggregate dust will drain, and to determine the amount of stabilizer needed. The German test procedure given in appendix A was developed using cellulose fibers. The applicability of this test procedure to other stabilizers is unknown.

- The author recommends ASTM D 4867, entitled "Effect of Moisture on Asphalt Concrete Paving Mixtures," or AASHTO T 283, entitled "Resistance of Compacted Bituminous Mixture to Moisture Induced Damage," for estimating moisture susceptibility.(1,3) These are commonly called the Root-Tunnicliff and Lottman tests, respectively.

- Tests for moisture susceptibility may have to be modified for SMA mixtures. For example, it is not known whether the air void levels specified by some tests for moisture susceptibility are applicable to SMA mixtures. Until more is learned about SMA mixtures, the author recommends that the air void level be between 5 and 6 percent in the test.

- Laboratory mixing studies were performed for GDOT using four stabilizers including a pelletized fiber. All four stabilizers appeared to mix with the aggregate and asphalt quite readily. This does not mean the wet mixing times for the stabilizers at a hot-mix plant will be equivalent, nor does it ensure that dispersion will be adequate in the plant-produced mixture. These can only be determined at the plant or if more realistic laboratory mixing devices are developed.

- The mixing and compaction temperatures for the Novophalt-modified binder used by GDOT in their SMA field study was based on the past experiences of GDOT. However, in these past experiences, the mixtures did not contain fibers or the high minus #200 dust contents used in SMA mixtures. These could further stiffen the binder. There was no firm basis for choosing mixing and compaction temperatures. A better method is needed for choosing temperatures.

- It may be beneficial to measure the volume of voids in compacted samples of the raw, coarse, SMA aggregates as performed in many open-graded mixture designs. This volume of voids can be compared to the combined volumes of the materials used to fill these voids plus the remaining air void volume after the SMA mixture is designed. For high stone-on-stone contact, the two should be approximately equal. The critical element is whether the volume of the fine aggregate and the amount of binder absorbed into the aggregate can be adequately taken into account.

- It should be determined whether the high binder contents and low air void levels of SMA mixtures compared to dense-graded mixtures help to resist age hardening, moisture damage, and fatigue cracking. (Promoters of cellulose fibers, which can provide the highest binder contents, emphasize the positive aspects of high binder contents and increased film thickness.)

- Preliminary European data indicate that the diametral moduli and indirect tensile strengths of SMA mixtures are lower than comparable dense-graded mixtures. This may be due to the thick binder films. Whether the diametral configuration is applicable to SMA mixtures needs to be determined.

APPENDIX A: DRAINAGE TEST

Instructions for Bitumen Segregation (Drainage) Test for Grit Mastic Asphalt (SMA) and Drainasphalt (Porous or Open-Graded)

Institut fur Materialprufung, Dr. Schellenberg Ing.GmbH, Leipheim

Approximately 2.2 lbm (1 kg) of asphalt mixture at 275 +/-1.8 °F (135 +/-1 °C) is placed into a dried, tared 800 ml glass beaker immediately after production using DIN 1996, part 20 (German Test Method) and weighed to the nearest 2.2 E-4 lbm (0.1 g). It is then stored for 60 +/-1 minutes at 338 +/-1.8 °F (170 +/-1 °C), covered by a tin or similar lid. Deviations from this storage period and temperature are to be noted in the report. After storage, the mixture is removed from the beaker and placed into a tared bowl by quickly turning the beaker upside down without shaking. The final weight of the mixture is then recorded. The temperature of the asphalt mixture will be less than 338 °F (170 °C) during the final weighing process. The percent segregation (drainage) is calculated as:

$$\text{Loss, percent} = \frac{100(\text{Original Weight} - \text{Final Weight})}{\text{Original Weight}}$$

Losses less than 0.2 percent indicated that no segregation should occur, although losses up to 0.3 percent are still acceptable. Losses greater than 0.3 percent indicate that segregation may be a problem.

Note: The storage temperature used in this procedure is based on the average hot-mix plant discharge temperature used in Germany.

REFERENCES

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