Designing Stone Matrix Asphalt Mixtures

Volume I - Literature Review

Final Report

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1.0 INTRODUCTION

The final report of the NCHRP 9-8 project on mix design of Stone Matrix Asphalt (SMA) mixtures consists of three volumes. Volume I contains a summary of literature, Volume II contains the research results, and Volume III provides the SMA mixture design procedure along with Quality Control/Quality Assurance procedures and construction guidelines for the construction of SMA.

Stone Matrix Asphalt (SMA) has been used in Europe since the 1960's but was not used in the U.S. until 1991. However, a large amount of literature has been published on SMA in the few short years of use in the U.S. A summary of the available literature on SMA is provided in this volume. This information should provide the reader with the latest information on SMA materials, mix design, construction, and performance.

2.0 INDIVIDUAL REVIEWS

Individual summaries or reviews of the various items that were found in the literature follow, for the most part, a chronological sequence, starting in 1985 in Europe. Although the European experience with SMA dates to perhaps 20 years before that, it was felt that there would be more benefit in focusing on the more recent developments of SMA rather than technologies and mix designs that have been superseded. SMAs continue to evolve in Europe. For example, although Germany is credited with the development of SMA, their 1984 specification was revised in 1990. In France, according to a 1992 Transportation Research Board (TRB) paper by Serfass and Samanos (33), thin wearing courses (30 to 50 mm) of Hot Mix Asphalt (HMA) were developed in the mid 1970s. Very thin wearing courses of SMA (20 to 30 mm) appeared about 1983 and have continued to evolve. The first SMA in the U.S. was placed in Wisconsin in 1991. Accordingly, the early literature reviewed is predominantly European. From 1991 onwards, the papers and articles are of mixed geographical origins.

In the individual reviews, comments by the authors are generally designated by text in square brackets. Such comments are intended to clarify the original text, occasionally to add information that was not contained in the original text but might be of advantage to the reader, and sometimes to draw the reader's attention to conflicting information between authors. Frequently, it was found that authors had not provided information that might be considered useful to asphalt technologists, especially where questions relating to mix design might occur. Such instances are also noted by text in square brackets.

1. Kast, O.E.
   Long-Term Experience with Splittmastixasphalt in the Federal Republic of Germany, 1985.

This paper provides a summary of SMA development in Germany. Gradation charts for SMA grades 0/11, 0/8, and 0/5 are given. Among the mix details, which are included in a convenient table, are:

1. Asphalt cement content 6.0% to 7.5% by mass. Grades 65 or 80 penetration.
2. Stabilizing additives 0.3% to 1.5% by mass.
3. Voids are in the range 2.0% to 4.0% under Marshall compactive effort. [Number of blows is not stated.]

The author writes that in the early years of SMA development, asbestos fibers were used as the binder carrier. However, that use was discontinued because of potential health hazards. By 1984, cellulose fibers, powdered rubber, rubber granules, synthetic silicic acid, *kieselgur* [a very finely ground silica], and polymers were in use.

Kast mentions that the stabilizing additive can be added directly to the mixer or admixed with the stone dust and fed to the mixer. In either case, he says, a slight extension of mixing time should guarantee adequate distribution of the additive. [The author does not advise a range of time for the extension of mixing.]

According to Kast, maximum placing temperature should be in the range 170°C to 200°C, and the minimum placing temperature should be between 120°C and 140°C, depending on the grade of asphalt cement.

The author cautions against the use of rubber-tired rollers and vibrating rollers for compaction and states that the finished surface course air voids should not exceed 6%.

2. *Slitlager av HABS*
   (Publication 1988:42 HABS -- Translation by Kjell Sardal 1991.)

This translation of the Swedish Construction specification 1988:42 HABS outlines the introduction of SMA from Germany in the late 1960s. At first, asbestos fiber was used as a binder carrier but this was discontinued because of health fears and the use of SMA decreased rapidly. However, SMA regained favor in the early 1980s with mineral and cellulose fibers, and powdered rubber as binder stabilizers.

The specification calls for work to be carried out on frost-free ground. A table linking SMA pavement type to average frost index is provided.

The salient points of interest gleaned from the specification are as follows:

AGGREGATE

1. Aggregate Flakiness Index is 1.45 or 1.4 max, depending on average daily traffic -- below or above 25,000. [However, traffic is not defined so it is not clear if the specification means standard 80kN axles or not. No test method for determining Flakiness Index is cited.]
2. Maximum Impact value is 50 or 45, again depending on traffic. [The test method is not mentioned.]
3. Maximum abrasion is 1.8 or 1.4 but on roads with speed limits over 70 km/hour, the value is 1.8. [No test method is given.]
4. Minimum crushed surface ratio is 50/20. [However, it is not clear what this means.]

PAVEMENT THICKNESS

1. Two types of pavements are given: SMA 12 (34-43mm), and SMA 16 (38-47mm). [The nomenclature appears to relate to the top size of sieve in millimetres that is used in screening the aggregate.]

BINDER CONTENT

1. Binder content is selected at 2% to 4% voids on laboratory samples compacted by Marshall. [The body of the translated text does not provide the number of blows. However, the original Swedish text quotes a method which is not given in the translation. No minimum binder content is mentioned in the body of the text. However, specification tables at the end of the document indicate minimum binder contents of 6.3% for SMA 16 and 6.6% for SMA 12. The binder grade is B 85 for both types of SMA.]

GRADATION

1. The paper shows gradation tables for both SMA mixtures. The original Swedish paper provides gradation charts in addition to the tables. Gradations generally follow the so-called "30-20-10 rule" [30% passing the 4.75-mm sieve, 20% passing the 2.36-mm sieve, and 10% passing the 75-µm sieve].

PRODUCTION AND CONSTRUCTION PHASES

The remainder of the specification deals with production, placement, and compaction. Noteworthy points are:

1. In batch mixers, the dry mixing time should be increased by 10 seconds over conventional mixes.
2. Specific instructions are provided for joint construction, including tack coating and sanding of longitudinal joints.
3. Compaction is by two rollers: static three-wheelers greater than 10 tons [presumably metric tons] or vibratory rollers greater than 7 tons. Compaction starts immediately after placement

and continues until average voids are 2% to 5% or individual values are 1% to 6%. [A sampling procedure is given.] The specification also calls for spreading and rolling of sand to eliminate skid hazards should there be an excess of binder.

3. *Report of the AASHTO Joint Task Force on Rutting*, American Association of State Highway and Transportation Officials, Feb 1989.

This report contains nothing on SMA. It is included here only for historical interest that during the existence of the Task Force, SMA was not considered.

4. Tappert, A.
Untersuchungen an einer Splittmastixasphaltdeckschicht -- *Folgerungen für die Praxis*, 1989

Tappert describes an SMA distress phenomenon that affected several construction projects in almost all Federal German states in 1988. The distress took the form of water being discharged from the friction course. An investigation revealed that although the aggregate gradations were very consistent and close to the required gradation, the binder content was extremely variable, the average of 12 samples being 6.2% but ranging from 5.7% to 7.3%. [The standard deviation (not given in the paper) was 0.52.] A performance test required the binder content to be 6.5%. Correspondingly, the voids content also fluctuated widely from 3.6% to 10.9%.

A confounding factor, says Tappert, was that the SMA was visually consistent. Neither the high binder areas nor the areas that displayed discharging water presented any discernible difference to the observer. From a practical aspect, it was thus virtually impossible to compensate for the low void areas by increasing roller passes in such areas.

The author provides several suggestions for changes in SMA mix design, and SMA production and construction procedures. He postulates that a minimum 6.5% binder content may be insufficient. [However, he does not suggest an alternative value.] Other suggestions are:

1. Filler content should be 10% minimum by weight.
2. The lower limit for stone greater than 5 mm should be increased to give 55% by weight for SMAs 0/11S and 50% by weight for SMAs 0/8S and 0/8. [See Ref. 10 for significance of S.]
3. Production temperature should not exceed 180°C.
4. The binder carrier (fibers) should be stored under dry conditions to prevent clumping and subsequent uneven distribution of the binder.
5. Dry mix the granular mineral material and binder carrier for 5 to 15 seconds. Remix all components for 5 to 10 seconds.
6. Compaction should be mainly in the static mode, using heavy tandem rollers or three-wheel rollers over 9 metric tons.
7. Do not use vibrating rollers with non-yielding subbases and thinner SMA layers.

8. Using rubber-wheeled rollers on SMA requires much experience and care because of the potential for mortar accumulation on the surface.

5. *EAPA Investigates Porous Asphalt and Stone-Mastic Asphalt Surface Layers in the EAPA Countries*, 1989

The second part of this brief publication provides a good summary of the use and state-of-the-art of SMA in eight European countries from 1970 through 1989. No activities were reported for Belgium and France, small amounts for Finland and Norway, a fair amount for Sweden, 1.5 million square metres for the Netherlands, and large amounts for Denmark and Germany. At the time of publishing, Sweden had tentative standard specifications, specifications were imminent in the Netherlands, and Germany had had specifications since 1984. The following points were noted:

1. MIX DESIGN
   Voids: 3% to 4%
   Stone content: 70%
   Bitumen content: 6.5% to 8.0%
   Filler content: 8% to 13%
   Fibers or stabilizers: 0.3% to 1.5%

2. MATERIALS

   Bitumen grades used were B65, B80, B200, and modified bitumens.

Stabilizing additives comprised mineral fibers in two countries, and cellulose fibers in four countries including Denmark, in which other additives of unspecied nature were used.

No special specifications on aggregate quality are given but the maximum particle size varies from 5 mm to 20 mm.

6. Rinckes, G.
   Steenmastiekasfalt op Plaatsen met Zware Belastingen, 1989.

In this article, the author indicates that from the initial use of SMA in the Netherlands in 1984, increasing amounts of the material are being placed. The three types are with top sized stone 6 mm, 8 mm, and 11 mm. These are designated SMA 0/6, 0/8, and 0/11 respectively. The mix materials are:

Crushed stone	65% for SMA 0/6. 70% for SMA 0/8 and 0/11.
Sand	Natural sand, or natural sand with crushed sand, or only crushed sand.

Filler	9 to 10%.
Cellulose fibers	0.3%
Bitumen	8% for SMA 0/6. 7.4% for SMA 0/8. 7% for SMA 0/11.

The author goes on to describe some applications of SMA on high load-bearing situations. These varied from industrial loading and parking areas, factory floors that are subject to fork lift trucks and concentrated storage loadings, to bus lanes and bus stopping areas, as well as military-purpose surfacings for accommodating tanks, and heavily loaded areas around container terminals. A few examples are:

<u>Factory floor SMA 0/6</u>

65% crushed stone 2/6
0.3% cellulose fibers
10% filler
7% bitumen 80 - 100 pen.
50% manufactured sand, 50% natural sand.

<u>Military purpose SMA 0/8</u>

73% diabase
0.3% cellulose fibers
9% filler with hydrated lime
7% bitumen 80 - 100 pen.
50% manufactured sand, 50% natural sand.

<u>Container terminal road SMA 0/11</u>

72% *graziet* [*graziet* is a sandstone (greywacke) with a high Polish Stone Value.]
0.3% cellulose fibers
8% filler
6.4% bitumen 80 - 100 pen.
50% manufactured sand, 50% natural sand.

The author stated that on the container terminal road project, the SMA layer thickness was 39.5 mm and a 3-year guarantee was required. He reported that after three years the road was performing well.

In his closure, the author said that for special situations, 100% manufactured sand and 45 - 60 pen bitumen might be used.

7. Ohlsson, S., and Sandin, A.
Stone-Mastic and Porous Asphalt Experiences from the City of Gothenburg, 1990.

The authors review the experience in Gothenburg resulting from the use of studded tires. SMA anti rutting measures began in 1981 and a keynote project in the Tingstad tunnel occurred in 1985. At that time, the normal dense-graded HMA, which had been placed in 1980, was completely worn through after five years, producing ruts of 25 mm to 30 mm. Over the succeeding years, 1985 to 1990, increased traffic (now running on the SMA) produced a reduced rut depth of about 17 mm. [The original dense graded surface is designated 80 HAB 12T 30% quartzite. The replacement was 80 Stabinor 12 50% quartzite. Presumably the quartzite quality was the same, although this is not stated in the paper. The "80" appears to signify 80 kg/m^2 coverage and the "12" seems to signify 12 mm maximum size stone. Stabinor is a trade name for SMA containing mineral fibers; an alternative is Viacotop, which is another trade name for an SMA containing cellulose fibers and rubber as the stabilizing binder carrier.]

Additional points of interest from the paper are:

MODIFIED BINDERS

Rut depths after two winters show no significant differences between SMA with 85 pen grade bitumen and SMA with a modified binder containing SBS type polymers. [It is not clear from the paper if mineral fibers (Stabinor) and cellulose fibers and rubber (Viacotop) were both used with the 85 pen bitumen.]

MAXIMUM STONE SIZE

Before 1986, 12 mm maximum size stone was used. In 1986, 16 mm maximum size stone was tried and produced favorable results. By 1990, thoughts were turning to the use of 22 mm maximum size stone.

POROUS ASPHALT

Part of the paper deals with porous asphalt.

SPECIFICATION

A tabular specification is provided at the end of the paper for both SMA and porous asphalt. [It is not clear if this is an end result type specification or some kind of laboratory mix. As the coverage rates are provided it is assumed that the criteria given are in-place requirements. If this assumption is correct, the void contents appear to be very low. No mix design criteria, such as compactive effort, are given other than what might be construed from the specification, which calls for 3% voids for Stabinor SMA and 2.5% voids for Viacotop SMA. Tolerances are not mentioned.]

8. Liljedahl, B.
   Heavy Duty Asphalt Pavement Pavements -- How do They Look? 1990

Liljedahl spends some time in this paper arguing the case for greater concentration of coarse aggregate in asphalt mixes. His argument leads him to conclude that it is nearly impossible to design conventional dense graded asphalt mixes with good shear resistance, good resistance to rutting, and satisfactory durability. The author's solution is to use SMA type mixes.

The remainder of Liljedahl's paper is a theoretical analysis in which he attempts to show that for stone-on-stone contact the mix needs to have about 80% coarse aggregate, which he defines as material above the 2-mm sieve. No supporting data for the mix design system is included in the paper.

9. Tappeneir, W.J.
   Splittmastixasphalt, 1990

This technical leaflet describes briefly the background, general principles, and basics of SMA mix design, production and placing.

The various points can be summarized as follows:

AGGREGATES

1. 3/8" or 1/2" aggregate are generally used.
2. Of the material retained on the #4 sieve, not less than 90% by weight should have one or more fractured faces and 75% by weight two or more fractured faces. Sixty to 70% by weight of the aggregate should be retained on the #4 sieve.

The fine aggregate should be manufactured sand.

FILLER

The minimum recommended filler content is 10% by weight. [No recommended gradation is given but the author says it should be as fine as practicable and a major portion of it should be embedded in the asphalt binder film.]

ASPHALT BINDER

A binder content in the range 6.5% to 6.8% is recommended for 3/8 inch aggregate. [No grade of binder is mentioned nor if the same range of binder content is applicable to 1/2 inch aggregate.]

ADDITIVE

The author says a combination of polyolefin and elastomer additives has been found to be particularly effective. Uniformity of binder film thickness can be further improved if 0.3% by weight of total mixture of short polyester or similar fibers are added.

PRODUCTION

Mixing time (batch or drum facility) may have to be increased by between 5 and 15 seconds over conventional mixes.

PLACEMENT

1. Static steel-wheeled rollers are preferred.
2. Vibratory rollers should be used sparingly (no more than two or three passes).
3. Pneumatic-tired rollers should be used only for finishing.

10. *Zusätzliche Technische Vertragsbedingungen und Richtlinien für den Bau von Fahrbahndecken aus Asphalt (4. Splittmastixasphalt)* 1984 (Revised 1990.)

This document is Section 4, Splittmastixasphalt, of the German Federal Ministry of Transport Specification. Given the relatively long history of SMA in Germany and the experience with the material in that country, it is worth considering.

The specification begins with a preamble in which a description of SMA is given. Along with such general comments as SMA being a high stone content, gap graded Hot Mix Asphalt, with a mastic filling the voids in the coarse aggregate, generic additive types are mentioned. These are organic and mineral fibers, acidic silica, or polymers in powdered or granulated forms.

According to the document, SMA is intended for use on all types of roads.

The finished SMA surface is treated with precoated or uncoated *Edelsplitt* 2 - 5 mm [a high quality, double crushed stone], or crushed sand, rolled into the surface while the SMA is still hot.

Also provided is a specification table from which the following has been adapted:

Splittmastixasphalt	0/11S	0/8S & 0/8	0/5
1. **Aggregate** (Crushed stone, manufactured sand, natural sand, filler)			
Gradation mm	0/11	0/8	0/5
Size less than 0.09mm % by weight	8-13	8-13	8-13
Size more than 2 mm " " "	70-80	70-80	60-70
" " " 5 mm " " "	50-70	45-70	≤ 10
" " " 8 mm " " "	≥ 25	≤ 10	-
" " " 11.2 mm " " "	≤ 10	-	-
Crushed sand/natural sand ratio	≥ 1:1	≥ 1:1	≥ 1:1
2. **Asphalt Cement**			
Grade	B65	B65 (0/8S) B80 (0/8)	B80 (B200)[1]
Content % by weight	6.5-7.5	6.5-7.5	7.0-8.0
3. **Stabilizing Additive**			
Content % by weight of mixture	0.3-1.5	0.3-1.5	0.3-1.5
4. **Asphalt-Aggregate Mix**			
Marshall Test Sample:			
Compaction Temperature °C	135 ± 5	135 ± 5	135 ± 5
% Voids	2-4	2-4	2-4
5. **Thickness of Compacted Layer cm**	2.5-5.0	2.0-4.0	1.5-3.0
Unit Weight kg/m²	60-125	45-100	35-75
Degree of Compaction %	≥ 97	≥ 97	≥ 97
% Voids	≤ 6	≤ 6	≤ 6

[1]Only in special cases

[In the above table, "S" stands for *schwer*, which means heavy. These mixes are intended for heavily trafficked pavements. It is worth noting that the filler requirement (passing 90µm sieve size) is 8 - 13% for all four grades of Splittmastixasphalt. The number of blows for the Marshall compaction effort is not given in the document. It is generally supposed by researchers in the U.S. that 50-blow Marshall is normally used in Europe. The above specification table implies that the compaction effort is determined by the compaction temperature (135 ± 5°C) and the air void range (2 -4%), the number of Marshall blows being immaterial. However, the German test standard DIN 1996, Part 4 also applies. This standard would seem to contol the compaction effort, which is generally understood to be 50 blows per face for SMAs. Voids in the mineral aggregate (VMA) and voids filled with asphalt (VFA) are not mentioned in the specification but are well known to asphalt technologists in Germany. Three gradation charts are also provided, the mandatory key sieve sizes being as shown in the table.]

11. J. Johansson
Drainage Asphalt Concrete (HABD) and Splitmastic Asphalt Cpncrete (HABS) - History, Technical Descriptions, Experiences and Future in Sweden, 1990

This brief paper seems to be concerned mainly about the wear of asphalt surfaces from the effects of studded tires. Summarized are two studies by the Swedish Road and Traffic Research Institute in the mid 1970s on the effect of studded tires on asphalt pavements. The studies revolved around two aggregate tests: the Aggregate Abrasion Value (AAV) and the Aggregate Impact Value (AIV). From these studies it was concluded that two types of wearing courses (Drainage Asphalt Concrete [HABD] and Splitmastic Asphalt Concrete [HABS]) could meet the requirements recommended in the studies. The paper goes on to discuss the two types and compares their gradations with each other and with the standard wearing course (HABT). The main points on SMA to be gleaned from the paper are:

1. The reason for the range of 6.0% to 7.5% binder content in SMAs is because different types of additives accommodate different rates of bitumen.

2. Fat spots noticed in SMAs are probably caused by excess binder.

3. The major findings from a small-scale field trial research project began in 1986 are also reported and are summarized as follows:

   (1) Increasing the maximum aggregate size in a standard dense graded mix from 12 mm to 16 mm decreases wear by 40%.
   (2) Using better quality aggregates with low AAVs and low AIVs reduces wear by almost 50%.
   (3) In comparing a normal dense graded mix with an SMA, both with good rock aggregate above 8 mm in size, the SMA showed 50% less wear during the first winter.

12. *Udbuds- og anlægsforskrifter, Almindelig arbejdsbeskrivelse Varmblandet asfalt*, 1990.

Three grades of SMA are listed in the HMA section of the Danish standard general specifications. [An English translation is available.]

The following points may be noted from this brief specification:

AGGREGATES

1.	Coarse aggregate (> 2 mm)	crushed rock.
2.	Fine aggregate (< 2 mm)	uncrushed gravel or sand.
3.	Flakiness value	≤ 1.45.
4.	Brittleness value	≤ 50.

[Test methods are not referenced.]

ASPHALT CEMENT

1. Grade — 60.
   Grade for ADT $<$ 4,000 — 85.

MIX DESIGN (MARSHALL) CRITERIA

1. VMA — $\geq$ 16%.
2. Voids — 1.5 - 4.0%.
3. VFA — 78 - 93%.

GRADATION

The following is an adaptation of the table provided:

Type	SMA 8	SMA 11	SMA 16
Maximum size mm	8	11	16
Nominal size at 90% passing mm	$\geq$ 6	$\geq$ 8	$\geq$ 11
Percent passing sieve			
5.6 mm	-	30-50	25-45
2.0 mm	25-35	18-30	15-25
Filler	$>$ 4	$>$ 4	$>$ 4

["Filler sieve" is not defined but is assumed to be 90µm. The nature of the filler is not specified -- this is customary in Germany also. Fibers are not specified but it is understood that cellulose fibers are mainly used at 0.2 to 0.3% of mix. Marshall compaction effort is not stated.]

13. *An Introduction to Stone Mastic Asphalt (SMA)*, 1991

This 2-page technical leaflet from ScanRoads, Sweden, provides a useful summary of the salient features of SMA using cellulose fibers. The leaflet is directed at the North American market and shows typical SMA gradations in U.S. standard sieve sizes for three aggregate sizes: 7/16 " (11 mm), 5/16" (8 mm), and 3/16" (5 mm).

Bitumen type and content vary from 65 penetration and 6.5% for the large aggregate to 80 penetration and 7.2% for the small aggregate. The cellulose fiber content is 0.3% for all gradations. Intended mat thicknesses vary from 2" (50 mm) to 0.6" (15 mm).

Target range for Marshall mix design voids is 2% to 4%, which, according to the leaflet, is important for achieving 4% to 6% voids in the finished pavement. [However, the number of blows for the Marshall mix design is not stated.]

The second page of the leaflet gives information on production and placement of SMA. Points noted are:

1. Additional mixing time of between five and 10 seconds is needed.
2. SMA discharge temperature should not exceed 180°C (356°F). Minimum placement temperature should be 150°C (300°F); and compaction should be completed before the SMA cools to below 130°C (265°F).
3. Compaction advice is interesting as two rollers (9 metric tons) are called for, with one roller being capable of vibration. The first pass is in the static mode, followed by two passes in the vibratory mode. However, warnings about decompaction and aggregate degradation are provided.
4. Sanding of the finished hot surface to improve skid resistance is also specified.

14. Scherocman, J.A.
Stone Mastic Asphalt Reduces Rutting, 1991.

In this article, the author provides an account of the first SMA pavement constructed in the United States. The project was a resurfacing contract for Wisconsin Department of Transportation (WIDOT) on I 94, west of Milwaukee. The mix design generally followed the German standards for SMA:

AGGREGATE

The aggregate was crushed limestone, consisting of 0.5-in. coarse aggregate, 0.375-in. coarse aggregate, 0.25-in. screenings and mineral filler.

GRADATION

The gradation followed the "30-20-10 rule" with 28% passing the #4 sieve, 20% passing the #8 sieve, and 11% passing the #200 sieve.

ASPHALT CEMENT

The grade of asphalt cement was 85-100 penetration. The binder content (asphalt cement and polymer) was 5.7% by weight of mix.

ADDITIVE

The additive was a polyolefin modifier, which was a type previously used by WIDOT. The additive was 7% by weight of asphalt cement.

VOIDS

Air voids were 3%.

MARSHALL

A modified Marshall mix design was used. [No details are provided in the article.]

Scherocman gives contact names for the mix design -- Jack Weigel of Payne and Dolan, and John Pope and Lynn Larson of WIDOT. The remainder of the article is devoted to production and placement information, of which the following is noteworthy:

1. A batch mixer was used.
2. The additive was fed to the weigh hopper via the reclaimed asphalt pavement (RAP) feed belt.
3. Mineral filler, constituting 7% of the aggregate by weight, was blown pnuematically into the weigh hopper of the facility.
4. Mixing temperature was normal -- 290°F. Both the dry and wet mixing cycles were unchanged from normal production for dense graded mixes.
5. Two vibratory rollers were used but both were in the static mode and both were operated within 500 feet of the paver. The target void content was between 6% and 8%.

This was generally achieved with between six and eight passes of the rollers.

15. Little, D.N., et al
A Preliminary Evaluation of Selected Factors Influencing the Performance of Stone Mastic Asphalt Mixtures (SMA), 1991.

Little and his coauthors begin this report with a general review of SMA and list specific requirements, with some reference to German specifications. In summary, these requirements are:

1. Coarse aggregate fraction (#10 sieve) greater than about 77%.
2. Hard and durable coarse aggregate.

3. At least 90% of coarse aggregate with at least one fractured face and 75% with two fractured faces is desirable. Cubical shape appears to be superior.
4. Filler (minus #200 sieve size fraction) should be between 8 and 13%.
5. The major portion of the minus #200 sieve size fraction should be less than 0.03 mm.
6. Important binder properties are tensile strength, cohesion, adhesion, and stiffness.
7. The use of polymer modified asphalt cements appears attractive. Reference is made to work at the University of Braunschweig, recommending nothing harder than AC-10 base asphalt for northern Germany.
8. Fibers are typically required to prevent drainage of the binder. Types of stabilizers include cellulose, mineral fiber, and polymer. Dosages are from 0.3 to 0.8% by weight of mixture. Fiber sizes vary from about 1/4 inch to less than 1/10 inch with European fibers typically being in the smaller end of the range.
9. Air voids are generally 2 to 5%, VMAs at least 16.5%, and VFA at least 78%.

This laboratory study had various objectives, primary ones being to evaluate the influence of a low density polyethylene (LDPE) modifier and to develop a knowledge base on SMAs. The main points to be derived are given below:

LABORATORY COMPACTION

Three types of compaction were used:

1. Texas Gyratory (ASTM D 3387).
2. Kneading (ASTM D 1561).
3. Marshall 50-blows (ASTM D 1559).

TESTING

Hveem stabilities, using a Texas test method, and Marshall stabilities, using the ASTM method, were determined. Air voids, VMA, and VFA were determined using Texas test methods. Other testing comprised:

1. Biaxial Indirect Tensile Testing (TEX-226-F).
2. Indirect Tensile Creep Testing (TEX-226-F).
3. Diametral Resilient Modulus Testing (ASTM D 4123).
4. Uniaxial Compressive Creep Testing.
5. Repeated Load Permanent Deformation Testing.
6. Triaxial Shear Testing.

The authors say that the last three tests listed above are not standardized tests. In these tests, samples were subjected to a TTI method of preconditioning before testing.

Drainage of the binder was evaluated using the Schellenberger runoff test [see Reference 35]. Both types of fibers were effective in preventing drainage from the aggregates. Fiber contents greater than 0.3% were not tried. Increasing fiber content from 0.15 to 0.3% increased air voids in compacted mixtures. Asphalt cement without fibers but modified with 6% LDPE (6.3% binder) was marginally acceptable. Without fiber or LDPE modification at 6.3% AC-20, drainage was approximately 15 to 20 times more.

CONCLUSIONS

The authors say that with binder contents more than 6.3% it is extremely difficult to produce mixes that are acceptable from an air voids standpoint when gyratory or kneading compaction methods are used. The authors believe it is not prudent to try to produce SMAs without modification of the asphalt cement. Conclusions listed in the report are:

1. SMA with AC-20 requires fiber stabilization of at least 0.3% by weight of mixture. Cellulose, mineral, or polyester fibers appear satisfactory.
2. SMA with LDPE modification of AC-10 base asphalt (4.5 or 5.2%) requires less fiber than AC-20 without LDPE modification. However, 0.3% is still recommended to give acceptable air voids under gyratory compaction.
3. SMA, with 6% LDPE modification of AC-10 without fibers, is substantially less susceptible to drainage than identical mixtures with AC-20 without fibers. However, drainage was still excessive and fiber addition at 0.3% is still recommended.
4. On the basis of the tests used, the best mix was AC-10 modified with 5.2% LDPE and 0.3% cellulose fiber. This mix met all air void, VMA, and gradation criteria with a binder content of 6.3%. The filler to asphalt ratio was 1.4.
5. Laboratory compaction method influences level of densification. Although 50-blow Marshall may be acceptable, most testing was done on samples that were prepared with Texas Gyratory compaction, which produced lower voids than Marshall compaction. The authors believe this indicates substantial compaction is necessary both in the laboratory and the field, especially for thick layers.
6. Without modification (such as with LDPE), asphalt cements of grades AC-20 and lower are not suitable even with fibers.
7. For warm climates, the authors recommend that AC-20, modified with LDPE and with fibers added, be used in future work. [It is not clear if this recommendation pertains to future laboratory studies or to field construction -- probably the former.]
8. Modified AC-10 or AC-20 should be superior to unmodified AC-30 or AC-40.

9. In terms of deformation potential, the test results showed that the SMA mixtures in the study were not superior to 100% crushed densely graded mixtures with LDPE-modified binder.
10. The authors believe that for the mixture evaluated in the study, substantially improved resistance to deformation can be achieved using AC-20 modified with LDPE.
11. A suitably stiff mastic will probably require polymer modification.

The authors conclude the report by recommending additional testing with harder grades of asphalt cement (AC-20 or AC-30) modified with LDPE.

16. Little, D.N.
Evaluation of Selected SMA Mixtures with Emphasis on Materials Used in the I-85, Georgia SMA Project, (Supplements Reference 15, 1991).

In this report (an undated draft final version), Little summarizes work done on SMA mixtures using materials supplied by Georgia Department of Transportation. Field cores and Falling Weight Deflectometer (FWD) data were also used in the study. The report is in five sections, the first one being background information on the work. The remainder can be summarized as follows:

AGGREGATES

Aggregates were #6 stone, #7 stone, #89 stone, and manufactured sand from one source. Mineral filler was from another source. Gradations used by the Texas Transportation Institute and other participating organizations, including NCAT, are given in an appendix. [The gradation of the filler is also provided in an appendix. It is 100% passing the #50 sieve, 96% passing the #100 sieve, and 79% passing the #200 sieve. Gradation below the #200 sieve was apparently not done.]

ASPHALT CEMENT

The asphalt cement was AC-30, modified with 5% LDPE.

STABILIZER ADDITIVE

Mineral fibers at 8% by weight of asphalt cement and hydrated lime at 1% by weight of the aggregate were added as directed by Georgia DOT.

MIX SPECIFICATION

The design followed Georgia DOT requirements of 50-blow Marshall and gradation criteria, which are supplied in an appendix. The optimum binder content is selected as the average of the binder content at maximum stability, maximum density, and air voids at 3.5%; but is also based on meeting VFA 65 - 85%, and Marshall Flow in the range 5 - 16 (1/100s inch).

The author says that although no VMA requirement was in the specification, the optimum mixtures achieved at least the minimum value of 15% as required by most European specifications.

ADDITIONAL TESTS

The additional testing was mainly uniaxial compressive creep. Some indirect tensile testing to failure and indirect resilient modulus testing (ASTM D 4123) were also done. Moisture damage was assessed using a modification of ASTM D 4867, the variations being preparation of the samples at air voids of between 4 and 6% for the fine-graded SMA and between 3 and 5% for the coarse-graded SMA instead of the stipulated 7% ± 1%. Among the conclusions reached by Little on these additional tests are:

1. With the given gradation band limits, it seems impossible to achieve higher binder contents than the original mix designs without reducing air voids below 2%.
2. Fiber content should be reduced to 6% by weight of the binder.
3. Little says that the aggregate used was soft and poorly crushed, which, he felt, might produce undesirable particle shape. [The LA Abrasion value of the aggregate is 35%. This is given in an appendix.]

EVALUATION OF FIELD CORES FROM I-85

Testing done on 14 surface SMA cores and 14 base SMA cores used the following methods:

Resilient Modulus (ASTM D 4123)
Marshall Stability and Flow (ASTM D 1559)
Hveem Stability (ASTM D 1560)
Indirect Tensile Strength (ASTM D 4123)
Indirect Tensile Creep (NCHRP Report 338)
Compressive Creep (NCHRP Report 338)

However, because the layers were relatively thin, most testing was done in the diametral mode. Four 6-inch cores were recored to provide 4-inch specimens.

Falling Weight Deflectometer (FWD) data was collected by Georgia DOT and provided for calculation of layer moduli.

The results of Georgia DOT's rutting test are also provided. [This test applies a loaded wheel to the specimen through a rubber hose, inducing a contact pressure of approximately 100 psi at a test temperature of 105°F.] Little says that the results indicate a highly rut-resistant mixture, which is a finding consistent with TTI's uniaxial creep analysis.

Little's other conclusions are:

1. Because the layers were relatively thin, Marshall and Hveem stability data are of questionable value.
2. The SMA cores have good resistance to fatigue and thermal cracking, probably because of the rich mastic.

SMA MIX DESIGN

The final section of the report provides the reader with a discussion of aspects that might be considered in designing SMAs. Little stresses that the nature of the filler is important and refers to previous work done at TTI on dilation of mixes. [However, no work on the SMA mastics was done in this study, although the author warns that it may be necessary to modify the asphalt cement in hot climates.]

Briefly summarized, the author's methodology and criteria on mix design appear to be:

18 - 23% passing 2 mm (#10 sieve).
60 - 70% crushed aggregate retained on the #4 sieve.
20 - 28% crushed sand.
10 - 12% filler (minimum 8% and minimum ratio of filler to asphalt cement 1.5).
Binder content 6 - 6.8% but variable.
Minimum VMA 16.5%.
Minimum air voids 3%.
Hveem Stability supplemented by Uniaxial Compressive Creep at 40 - 70 psi (NCHRP 338).
Diametral Resilient Modulus (ASTM D 4123) to meet NCHRP 338 criteria.
Fatigue at 41, 77, and 104°F (NCHRP 338).

17. *Fiber and Fill: a Key to Super-Asphalt Success,* 1991.

The focus of this article is on one type of cellulose fiber, manufactured in Germany and marketed in the U.S. by ScanRoad Inc. According to the unidentified author, the following features apply:

Average length of fibers	1.1 mm.
Average thickness	0.045 mm.
Average bulk density	1.5 to 1.9 pounds per cubic foot.
Approximate dosage	0.3% by weight of SMA mix.
Packing	2.2 pound (1kg) press packs in low melting point polyethylene.

The fiber is also available in pelletized form as a 50/50 by weight fiber/bitumen granule. The pellets have the following description:

Color	Dark grey.
Shape	Cylindrical.
Approximate length	0.24 inches.
Approximate diameter	0.16 inches.
Approximate bulk density	28 pounds per cubic foot.
Approximate dosage	0.6% by weight of SMA mix.
Packing	2,200 pounds on pallets or in bulk.

The author says loose cellulose fiber can be fed directly into the weigh hopper or pugmill at 6 pounds per ton of mix in batch mix operations; for drum mixers, pellets can be fed through the RAP (reclaimed asphalt pavement) entry port at a rate of 12 pounds per ton. An advantage of the pelletized form is that the fibers are not carried out into the baghouse in the exhaust gas stream.

Mineral fiber, said to be manufactured from basalt aggregate under a Swedish patent, is also mentioned. It is reported in the article that in Swedish SMA projects, mineral fiber is used about half the time and cellulose fibers for the other half. Polymer modifiers are sometimes used along with fibers in Europe; in Germany, this approach is frequently used. In a small number of projects in Germany, polymer modified asphalt without fibers was used.

18. Hoppe, W.
Der Splittmastixasphalt - eine Bauweise mit vielen Anwendungen, 1991.
[Splittmastixasphalt - A construction Method with Many Applications.]

In this paper, Hoppe discusses the use of SMA in Baden-Württemberg through the German specification ZTV bit-StB 84 (Reference 10). SMAs are adaptable to high traffic densities and SMA overlays are much used as an alternative to dense-graded HMA on autobahns.

The author gives a general account of the principles of SMA, stressing the high quality crushed stone skeleton, thick films of binder (especially surrounding the stone-on-stone contact areas), and low voids in the mix (which results in less hardening of the asphalt cement).

Initially, asbestos fibers were used to prevent draindown of the binder but these were superseded by more environmentally acceptable stabilizing additives.

Through trials of various mix compositions, SMA was found to optimize the properties of shear resistance, density, and cohesive/adhesive strength best.

Hoppe describes how on Bundesstraße 10 (Federal Road 10) the portland cement concrete was replaced by HMA, the binder layer of 7% voids being an SMA type of mix. [A picture accompanies this part of the text and depicts heavy traffic on a dual 2-lane highway.]

Another use of the versatile SMA has been as the initial protective layer on bridge decks.

The author indicates that SMA can be applied in variable thicknesses, according to requirements. Typically, the thickness may be anything from 2.5 to 5 times the maximum particle size. Hoppe points out the economic advantage of placing thin layers of SMA for renewing skid resistance on existing surfaces, which would otherwise require a 40-mm thick overlay of dense-graded HMA.

Part of Hoppe's paper deals with the noise-abating properties of SMA [See also Reference 75], this being an important property in some instances, for example, where there is heavy traffic in the vicinity of residential dwellings. Apparently Hoppe believes the noise reduction capacity comes from the surface texture characteristics of SMA. To illustrate the point, Hoppe shows surface texture variation profiles for an old dense-graded 0/11 (11 mm top size stone) pavement compared with that of a new 0/5 SMA. There are many more deeper valleys for the SMA profile than the dense-graded mix. The noise reduction may be as much as 2.5 dB(A).

In an interesting application, Hoppe relates how SMAs with "transparent" binders have been used for demarcation of traffic zones and special areas.

19. Richter, E.
Vergleichende Untersuchungen an stabilisierenden Zusätzen für Splittmastixasphalt, 1991.
[Comparative Tests on Stabilizing Additives for Splittmastixasphalt.]

Richter refers to the German specification for SMA, ZTV bit-StB 84 (Reference 10), and notes that the stabilizing additive can be 0.3 to 1.5% by weight of mix. In this laboratory evaluation, he considers three fiber products: cellulose, mineral wool, and glass fiber; two fine-particle flours: synthetic silicic acid and calcium hydrosilicate; and one polymer: an amorphous thermoplast in granular form. The author explains the purpose of stabilizing additives (prevention of draindown of the binder), and notes the additional advantages of thicker binder layer film or asphalt mastic layer, and increased cohesion of the binder.

The author notes that additive stabilizers (with the exception of polymers) have large surface areas. Polymers, Richter says, dissolve in the asphalt cement and change the viscosity of the material but do not create additional binding.

For the laboratory tests, Richter used a standard 0/11 [top size 11 mm] SMA with various additive stabilizers of the above-mentioned types. The tests used for the evaluation were:

ADDITIVE STABILIZERS

Special fillers	- Stabilizing Index
	- Binder demand range
Polymer	- Rheological data

[The Stabilizing Index appears to be done by using the Ring and Ball (R&B) test on a B 200 bitumen with increasing amounts of filler until an increase of 20 C degrees in the original R&B value is achieved.

In the Stabilizing Index Test, Richter found little difference among all the stabilizing additives (including the granular polymer) except for one of the fine-particle flours, which required a significantly larger amount of material to meet the 20 C degree increase and a powdered limestone filler, known as normal filler, which had the highest demand of all. [Richter does not say if the fine-particle flour was the synthetic silicic acid or the calcium hydrosilicate.]

For the Binder Demand range, Richter used a variation of a method attributed to Schulze in 1964. The procedure is not clear from Richter's paper.

In the Binder Demand tests, Richter found two of the fibers performed better than any other stabilizing additive. The limestone powder performed the poorest. [Richter does not identify the three fibers or the two fine-particle flours in his table of results.]

By rheological data, Richter means that the following tests were done on the B 80 bitumen and on the B 80 modified with 7% polymer:

Ring and Ball Softening Point
Penetration
Fraas Break Point
Penetration Index
Kinematic Viscosity at 60, 90, 135, and 200 °C
Adhesion [or coating] test

The effect of the 7% polymer was to increase the R&B value, decrease the penetration, reduce the Fraas Break Point from -14 to -20°C, change the Penetration Index from +0.22 to +0.56, and increase the viscosity at 60°C by a factor of almost 3. The viscosity at 200°C was only slightly increased.

SMA TESTS

Schellenberg Draindown Test [See Reference 35]at 170°C
Marshall Stability at 60°C
Densification at 135°C

Heat stability	- Pressure, Swell Test at 45°C
	- Rutting Test at 65°C
Cold Temperature	- Fatigue Bending at 5°C
	- Deep Temperature Cooling

The recipe for the SMA 0/11 was:

Bitumen B80 grade	6.5% by weight
Total filler	9.0% by weight
Manufactured:natural sand	2:1

Gabbro-Edelsplitt [High quality crushed gabbro]	72% by weight
Coarse crushed stone	36.8% by weight

The total filler of 9% consisted of limestone powder and various quantities of other fillers. A control mix with 6.0% bitumen B 80 was used. All other SMAs had 6.5% B 80 content except for the polymer-modified SMA, which had 6.1% B 80 and 0.4% polymer for a total binder content of 6.5%.

In the Schellenberg Test, one of the fibers performed better than any other stabilizing additive.

The Marshall stabilities for all the mixes ranged from 6.6 to 7.7 kN, proving, as noted by Richter, that Marshall stability is of little value in evaluating SMAs. [As a point of interest, the SMA with the limestone filler had the highest stability value.]

The Densification Test is not clearly understood from the paper. It appears to be based on using Marshall compaction effort at 100 blows per face to give what Richter calls a D-Value; and measuring air voids after a compaction effort of 50 blows per face. Both compactions are done at 135°C. [Richter gives a reference to Renken's dissertation in 1980 for details of the method. However, at 100 blows per face, there undoubtedly will be aggregate fracture and one has to question whether or not the SMA is anything like the original intended gradation.] Richter found little difference in the D-Value results for the 100 blows per face specimens. The air voids results for the 50 blows per face specimens range from 1.9 to 3.0%, with two of the SMAs with fibers [types not identified] representing these extremes.

For the heat stability evaluation, Richter used a dynamic loading test attributed to Kast and von der Weppen in 1978. The test is conducted at 45°C and measures deformation according to loading cycles. One of the fiber SMAs and the polymer modified SMA performed best. They were about the same after 16,000 cycles. However, one of the other fiber SMAs performed the worst of all mixes. [No identification by the author is given.]

A French rutting test was performed on only the polymer-modified SMA and one of the fiber SMAs [which is not identified]. The polymer-modified SMA had the superior performance.

For cold temperature behavior, Richter cools SMA blocks (40x40x300 mm) at a temperature reduction rate of 8°C per hour. [The procedure is attributed to a paper in French by Guericke dated 1968.] The breaking temperature range was -31 to -33°C and the breaking stresses were 3.4 to 3.8 N/mm.

In a bending beam fatigue test at 5°C, one of the fine-particle flour SMAs performed best. This was followed closely by the polymer-modified SMA. One of the fiber SMAs performed poorest.

Richter concludes that the German specification is not enough to characterize SMAs and that additional tests are needed.

[Based on the paper, it was unclear which fiber, etc. was performing best according to the tests conducted. As some of the test methods are unfamiliar, it is difficult to know how they relate to performance.]

20. Bukowski, J.
Stone Mastic Asphalt and Evaluation Project No. 18, 1991.

This document is a work plan by the FHWA for potential users of SMA. The intention is to duplicate and verify European SMA design and construction experiences in the U.S. with the hope that by 1994 there would be sufficient experience to determine the overall acceptability of SMA.

The report begins by providing background information on the European Asphalt Study Tour (EAST) in 1990 and the subsequent visit to Europe in 1991 by a technical group, specifically to gather further information on SMA.

In the report there is a summary of the five SMA projects that were constructed in the U.S. in 1991. This summary is reproduced below.

During the evaluation of these five projects, a number of preliminary findings were made. Of note among these are:

1. Material passing the #4 sieve should be about 30%.
2. The particle size distribution of the mineral filler is important and should be limited to less than 3% of the total aggregate finer than 20µm. [Later in the report, Bukowski says that commercial filler passing the #200 sieve should not have more than 20% finer than 20µm.]
3. Excessively flat and elongated particles should be eliminated. Bukowski suggest a maximum on any aggregate stockpile of 20% material of a ratio of 3 to 1, length to width.

SMA PROJECT GUIDELINES

Project guidelines are given for states desirous of committing to an SMA test and evaluation project. A prerequisite is high quality crushed stone. Mix design should be by Marshall, using 50-blow compaction with air voids between 3 and 4%. Among the construction operations requirements are:

1. Mix temperature should be about 325°F but not more than 350°F.
2. Steel-wheeled rollers should be used. Pneumatic-tired rollers should not be used.
3. The SMA should be compacted to about 6% voids, monitoring with a nuclear density gauge and verifying by cores.
4. Produced mix should be checked using Marshall.

AGGREGATES

Bukowski says that current (1991) SMA projects are generally following the German ½ inch gradation band:

95 - 100% passing ½ inch sieve.
30 - 35% passing #4 sieve.
20 - 25% passing #8 sieve.
10% passing #200 sieve.

The author says that the practice in Europe has been to use granite, basalt, diabase, porphyry, and quartzite aggregates; limestone, sandstone and similar stones are not used. Typical aggregate requirements in Europe are 90 to 100% by weight with one or more crushed faces, 75% with two or more crushed faces, and manufactured sand. Crushed faces appear to be important and the intention is to retain this requirement. Bukowski points out that in Germany and Sweden, special tests for resistance to fracture and abrasion are used. The abrasion test is not the LA Abrasion Test (AASHTO T 96), although it is hoped it will be satisfactory in the U.S. An LA Abrasion Test value of not greater than 30% is preferred. Other preferred aggregate properties are:

Coarse aggregate conforming to AASHTO M 283 for Class A aggregates unless otherwise stipulated.

1. Flat and elongated particles (measured on No. 4 sieve retained material) ASTM 4791

3 to 1	20% max.
5 to 1	5% max.

2.	Sodium sulfate soundness loss	
	(5 cycles) AASHTO T 104	15% max.
	If magnesium sulfate used	20% max.
3.	Absorption AASHTO T 85	2% max.
4.	Coarse and fine durability index AASHTO T 210	40 min.

Fine aggregate should be 100% crushed, conforming to AASHTO M29.

Sodium sulfate soundness loss (5 cycles)	15% max.
Liquid limit AASHTO T 89	25 max.

Gradation Target Range
(Percent by weight passing sieves, AASHTO T 27 and T 11)

Sieve Size	Percent Passing
3/4 in.	100
1/2 in.	85 - 95
3/8 in.	60 - 75
#4	25 - 32
#8	18 - 24
#30	12 - 16
#50	12 - 15
#200	8 - 10
20µm	less than 3*

*To be controlled from a combination of aggregate and mineral filler taken from representative stockpile samples.

ASPHALT CEMENT

In Europe, 60 - 80 penetration grade is the typical asphalt cement. Although this is approximately equivalent to AC-10 or AC-20 grades in the U.S., adjustments may have to be made for extreme temperature conditions in some parts of the country.

MIX DESIGN

While conceding that further work needs to be done, the author says that current projects used 50-blow Marshall compaction. He also says that traditional values of stability and flow appear to be less relevant for SMAs than they are for conventional dense graded HMA. A summary of data for each of the five state projects completed in 1991 is included as an attachment. A model specification is also included as an attachment. At the time when it was drafted, the suggested SMA mix requirements were:

Marshall (AASHTO T 245)

1.	Voids	3 - 4%
2.	Asphalt content	6% min.
3.	VMA	17 min.
4.	Stability	1400 lbs., min.
5.	Flow	8 - 16 (1/100 in.)
6.	Compaction	50 blows each face
7.	Schellenberg Draindown	0.3% max.

Standard test procedures for the above are referenced. The user is also referred to notes that say the Marshall stability requirement may be modified and a failing measurement should not be the only reason for rejecting an SMA design.

FIBER STABILIZERS AND MODIFIERS

Fibers are used in nearly all German and Swedish SMAs. In projects in Wisconsin and Indiana, asphalt modifiers were used but without fibers; such SMAs typically have an asphalt content of 0.5 to 1.0% less than comparable SMAs with fiber. Bukowski says that critical fiber properties are being investigated and he includes an attachment that shows the trend of investigations. Details of the Schellenberg Draindown Test are also provided in the attachment. Sources of fibers are given in another attachment.

21. Pryor, C.
Stone Mastic Asphalt: A Potential Rutting Solution, 1991.

In this technical news article, Pryor explains the derivation of SMA in Europe from its initial purpose as a surface course to resist damage from studded tires to its more recent role as a rut-resistant mix. He describes the salient features of SMA, noting that the coarse aggregate is typically 100% crushed stone with a top size of ½ to ¾ inch and that the percentage of fine aggregate is noticeably less than conventional U.S. mixes. He also provides information on the FHWA/Michigan DOT SMA demonstration project, dated August 6 - 7, 1991, noting that crushed stone was transported over 300 miles to the plant site. Pryor points out that while this stone was a high quality granite, one fraction had to be reprocessed because of too many flat and elongated particles.

In the remainder of the article, the author provides some information on production, placing and compaction. He noted that steel-wheeled rollers had to work close to the paver, which was operated at 10 to 15 feet per minute, and that 98% of target density (as measured by nuclear gauge) was achieved within 10 minutes.

The article includes mix data in an accompanying chart showing:

MATERIALS

Aggregate: 100% crushed (98.9% igneous, 1.1% sandstone)
Asphalt cement: AC-20
Cellulose fiber: 0.3%

MIX DATA

Asphalt cement @ 6.5% optimum
Field control density: 151.1 pcf
Specific gravity: 2.42
Air voids: 3%
Stability: 1074 [Presumably Marshall pounds.]
Flow: 8.7 [Presumably 1/100 inches.]
VMA: 18.2%

GRADATION

The gradation is provided in the following table:

	Percent Passing	
Sieve Size	Job Mix	Specification Range
¾ in.	100.0	100
½ in.	94.1	90-100
⅜ in.	72.9	54-80
#4	36.1	30-45
#8	24.6	20-30
#16	19.2	16-26
#30	15.9	13-26
#50	13.8	10-22
#100	12.3	9-19
#200	10.4	8-13

22. Drake, R.
Asphalt-Mix Technology Puts Emphasis on Aggregates, 1991.

In this brief article, the author refers to two SMA projects in Michigan in 1991 and draws attention to a view (attributed to Michigan Department of Transportation) that higher costs may be experienced with SMA in comparison with conventional dense-graded surface mixes. The additional cost is said to be about 20 to 30%. Briefly, the reasons cited for the higher costs are:

1. The higher quality materials required for SMA cost more to produce.
2. A longer mixing time is needed in the production phase.
3. Slower paving speeds.
4. More intensive quality control is needed during the production and placement phases.

The author says that Michigan DOT paid an extra $30 per ton in haulage to obtain suitable aggregate from 200 miles away for the projects. He also points out potential problems if sand and gravel deposits do not contain sizes large enough to give crushed faces for the coarse aggregate and crushed sand requirements in the specification. In respect of these points, the author quotes an NCAT 1990 rutting study for Pennsylvania DOT in which it is concluded that there should be at least 85% coarse aggregate particles (retained on the #4 sieve) with two or more fractured faces and at least 75% manufactured sand -- 100% if possible.

23. Eaton, M.
Wisconsin Tests New Stone Mastic Asphalt Technique, 1991.

This is a news item on the first SMA placed in the USA. The work was a demonstration project, placed on July 10, 1991 in Waukesha County, on the I-94, which is reported to be one of the most heavily traveled roads in Wisconsin.

24. Carrick, J., et al.
Development of Stone Mastic Asphalt for Ontario Use, 1991.

Citing the success of SMA overseas and initial satisfactory demonstration trials in Canada in December 1990, the authors describe in this paper the preliminary SMA mix designs used and the subsequent design developed for further sections that were placed in June 1991.

Like many other papers that deal with a relatively new topic, this one contains an opening description of SMA. The authors classify SMA as being a gap graded HMA of 3% voids, with passing 2 mm limited to about 20%, all aggregate 100% crushed, and the filler about 10% passing 75µm. According to the authors, the asphalt cement is typically polymer modified; and the stabilizing additive (if needed) is typically about 0.3% mineral, glass, or cellulose fiber. Polymer modified asphalt cement content is typically 1.0 to 1.5% greater than that of a conventional HMA with the same aggregates. Filler (finer than 90µm) to asphalt cement ratio is higher than the 1.2 ratio recommended by the FHWA for conventional HMA dense graded mixes. The typical compactive effort is 50 blow Marshall. [The authors provide a brief summary of advantages, disadvantages (cost and lack of experience), and technology from European and Japanese experience with SMA.]

For the first trial sections, nominal maximum size aggregates of 13 mm for the surface course (SMA 1), and 19 mm for the binder course (SMA 2) were used. A notable difference from the authors' acknowledged SMA design criteria was the use of a 75 blow Marshall compactive effort for SMA 1 and SMA 2 mixes for 3% voids target. Designs were done with 60/70 penetration polymer modified asphalt cement but 85/100 penetration grade was used in the field. An SMA 3 mix design of 50 blow Marsahll and 4% voids was also used.

An interesting point is that fly ash filler [no details provided] was used in the SMA 1 and SMA 2 trials but a ground dolomite filler [again, no details provided] was used in the SMA 3 work. For the SMA 3 mix design, 50 blow Marshall and 4% voids were used.

In a table in the paper, SMA 1 and SMA 2 are the initial trial designs, and SMA 3 is the later design. [VMA, stability, and flow properties for all three mixes are given but do not appear to be requirements of the specification.]

Slabs removed from the SMA 1 and SMA 2 trial sections, and the existing pavement (as a control specimen) were subjected to a standard Ontario Ministry of Transport rutting test. The SMA 1 surface course performed slightly better than the SMA 2 binder course but both of them significantly outperformed the existing pavement section.

In the production of all three mixes, problems were encountered with glass fiber dispersion and uncoated fiber balls were evident in some batches. The authors indicate that currently, cellulose fibers are being considered.

The authors conclude from the early excellent performance of SMA 3 that mixes should be designed at 50 blow Marshall per face at 135°C and 3% voids. [VMA, stability, flow etc., are not mentioned.]

At the time of writing the paper, a Nottingham Asphalt Tester was being installed to measure resilient modulus, resistance to permanent deformation, and fatigue.

25. Warren, J.M.
SMA Comes to the USA, 1991

This brief article contains a description of the essential features of SMA and provides summaries of the mix properties of four SMA projects that were placed in Wisconsin, Georgia, Michigan, and Missouri in 1991.

In comparing U.S. and European SMA mix designs, Warren draws attention to the voids analysis procedure via the Marshall method of mix design used in the U.S. while the technique in Europe typically follows specific gradations and recipe-type approaches.

Warren had the advantage of visiting the first four SMA projects during construction in 1991 in the U.S. He observed that all SMAs could be worked by hand -- but with difficulty because of the stiffness of the mixes. Commenting on the Missouri Project, Warren noted that two SMAs were placed at night with no problems. The first SMA contained cellulose fibers (0.3% by weight of mix), the second contained mineral wool (0.5% by weight of mix).

26. *Report on the 1990 European Asphalt Study Tour*, 1991.

The European Asphalt Study Tour (EAST), comprising a 21-member group of people who represented state and federal government, SHRP, TRB, and industry, embarked on a 14-day study tour of six European countries in 1990. One of the objectives was to review and evaluate foreign pavements and asphalt technology.

A section of this report addresses SMA. In addition to providing a familiar description of the salient features of SMA, the report includes a gradation chart in which the gradation of a conventional U.S. HMA gradation is compared with a typical SMA.

The report reviews SMA design in several European countries.

GERMANY

In referring to the German specification, the report indicates that SMA mix designs are not carried out in the same sense that mix designs are conducted in the U.S. Instead, a recipe-type approach from standard designs is followed. The report states that Marshall specimens are prepared at 50 blows per side for several bitumen contents with a selected aggregate gradation and compacted at 135 ± 5°C. The optimum bitumen content is taken to be the one that produces 3% air voids in the compacted mix.

In Lower Saxony, the practice is to begin with a bitumen content of 6.8% and then to check if the compacted mix has an acceptable air void content.

In both the above cases, it seems that further test requirements such as Marshall stability, creep compliance, and resilient modulus are not necessary.
[The German specification is reviewed under Reference 10.]

SWEDEN

The report shows gradation charts for Swedish SMA top sizes 12 mm and 16 mm (called HABS 12 and HABS 16 respectively) in two charts and presents some specification details of the Swedish National Road Administration (SNRA). [This specification is reviewed in greater detail under Reference 2.]

In addition, the report provides information from Swedish contractors, many of whom stressed the importance of the 2 mm sieve size in SMAs. Contractors strongly recommended not more than 20 to 23% passing the 2 mm sieve.

DENMARK

According to the report, SMA is not used as widely in Denmark as it is in Sweden or Germany. Gap-graded HMAs, similar to types placed in the United Kingdom, are used on roads carrying heavy traffic.

Although no SMA design information is given in this section of the report, the group did inspect an in-service pavement and gleaned the following:

1. The 40 mm wearing course was said to have a gradation conforming generally with the SNRA limits for HABS 12 mixes.
2. Cellulose fibers comprised 0.25% of the mix.
3. The bitumen [base grade not identified in the report] was modified with an SBS polymer, comprising 6% of the binder. The polymer modified binder content was 6.9% by weight of the mix.

[The Danish specification is reviewed under Reference 12.]

FRANCE

In the section dealing with France, the writers of the EAST report state that SMA is not used in France. The chief concern is said to be the difficulty of achieving the desired micro-texture for skid resistance. [This appears to be at variance with a subsequent report (see Reference 33), which indicates that SMA for thin friction courses began in France in 1983 with a previous history of development from the mid 1970s.]

The EAST report provides the following information on the use in France of two types of gap graded mixes that appear to meet the criteria for SMAs:

THIN SURFACING

Layer thickness	40 mm approximately
Aggregate	100% crushed
Asphalt cement grade	40 - 50 or 60 - 70 pen
Asphalt cement content	5.7 to 6%

[It is not clear if the asphalt cement is modified or not. However, the writers say that France uses more polymer-modified asphalt than any other country in Europe, but only in surface courses. About 7% of all asphalt mixes are polymer-modified.]

The report indicates that the French claim excellent rut resistance and skid resistance with this mix.

VERY THIN SURFACING

This is similar to the thin surfacing mix but the thickness of the layer is about 25 mm. The writers state that the asphalt cement [grade not stated] is modified with polymers, rubber, or fibers. The asphalt cement content may go up to 7%. A heavy tack coat of polymer modified emulsion is used.

27. Kuennen, T.
Split Mastic Asphalt -- Next Overseas Import? 1991

This is a one-page news item on SMA, referring to the European Asphalt Study Tour (EAST) and providing a summary of the findings by tour participant Francis Francois.

28. Eaton, M.
Over 300 Gather for SMA FHWA/Michigan Demo Project, 1991.

This news item provides background information leading to the above project on August 6 and 7, 1991 on Michigan Route 52. The article contains also information on the source of fiber used, the paving contractor and construction equipment, and comments by John Bukowski in which he compares the SMA work with other projects done in Georgia and Missouri.

29. Parsons, R.H.
European Paving Technology Spurs American Thought, 1991

This is a technical news item on the FHWA/Michigan DOT SMA demonstration project on State Route 52 in Michigan.

30. Rinckes, G.
Dunne Deklagen van Steenmastiekasfalt, 1991.

In this article, the author deals with thin surfacing layers of SMA -- 15 to 25 mm in thickness, with a coverage of 35 to 60 kg/m². Rinckes explains the differences between a typical 6-mm top size aggregate dense-graded HMA and an SMA of the same top size aggregate:

	SMA 0/6	Asphalt Concrete 0/6
Crushed stone	65%	50%
Sand	25%	43%
Filler	10%	7%
Cellulose fibers	0.3%	
Bitumen	8%	7%

The above figures are approximate values.

The author compares the stone skeleton structure of SMA with the "floating" coarse aggregate particles in regular dense-graded HMA. He indicates some required characteristics in the 1990 Standards:

1. Crushed stone -- must be able to resist crushing under rolling compaction.
2. Sand -- natural sand or a mixture of natural and manufactured sand.
3. Filler -- limestone flour.

Rinckes says he has no special remarks to make about storage and transportation of SMA.

On compaction, Rinckes notes that thin HMA layers cool more rapidly than thick layers. For thin dense-graded mixes, this could pose a problem in achieving necessary compaction but for SMA mixes there is no problem. Compaction is 97% for layers 15 mm and thicker, and 96% for layers thinner than 15 mm. Two rollers are used: a three-wheel roller of about 10 metric tons and a vibratory tandem roller of 6 to 8 tons. The vibrating roller is operated behind the paver. Rinckes cautions against the use of the machine in the vibratory mode.

31. Georgia Department of Transportation.
Stone Mastic Asphalt, 1992.

This report on Georgia DOT's first SMAs provides mix design and construction details for the research project whose test sections were placed on the I-85. The research considered coarse SMA, fine SMA, and a porous European mix. [Some aspects of the work are covered also under other references as shown below.]

Based on Georgia DOT's initial mix designs, several organizations made recommendations to Georgia DOT on the fine and coarse mix designs that were being planned. These organizations were:

1. Texas Transportation Institute (TTI). [Reference 15.]
2. Laxa Bruk, Sweden.
3. FHWA. [Reference 35.]
4. National Center for Asphalt Technology (NCAT). [References 40, 48.]

MATERIALS

1. The coarse SMA aggregate had a Los Angeles abrasion test value of 35%.
   The fine SMA aggregate had a Los Angeles abrasion test value of 20%.
2. The mineral filler was marble dust with particle sizes in the range of 30 to 300µm.
3. Hydrated lime was added at 1% by weight of aggregate.
4. The stabilizing additive was mineral fiber, added at approximately 8% by weight of asphalt cement.
5. A polyethylene modifier was used in the study. The dosage rate was 5% by weight of asphalt cement.
6. The grade of asphalt cement was AC-30.

MIX DESIGN

1. Compactive effort was 50-blow Marshall.
2. Laboratory mixing temperature was 325°F.
3. Laboratory compaction temperature was in the range 310 to 325°F.

Three tables are provided in this section, providing a sample of mix designs that were done by Georgia DOT, TTI, Laxa Bruk, FHWA, and NCAT for the fine and coarse SMAs.

The remainder of the report deals with the production and placement of the SMAs. The job mix formula for the fine SMA is included. Average gradations for the plant mixes are also provided. Loaded wheel testing results of plant mix and roadway cores are provided. The coarse and fine SMAs performed significantly better than conventional mixes. [No details of the conventional mixtures are given.]

32. *Supplemental Specifications, Georgia Department of Transportation*, September, 1992/July, 1993.

Several modifications of the Georgia Department of Transportation's Standard Specifications were made between September 14, 1992 and July 16, 1993. Some of the items relate to SMA in Georgia.

On September 14, 1992, a subsection 8 was added to Section 400.03.B. This relates to the fiber supply control systems and among other conditions requires that the delivery of the fibers be controlled to within ±10% of the amount of fibers required.

Table 400.05.C.1. designates thicknesses for the department's fine and coarse SMAs as follows:

	SMA-F	SMA-C
Minimum Layer Thickness	1-1/8 in.	1-1/2 in.
Maximum Layer Thickness	2 in.	2-1/2 in.
Maximum Total Thickness	4 in.	--

Section 400.05.C.3. specifically excludes the use of pneumatic-tired rollers on all SMA paving.

In Section 400.05.E. there is a condition that SMA mixtures shall be subject to the same density requirements as mixtures requiring 75-blow Marshall designs.

Also on September 14, 1992, Section 820.02 (test requirements for polymer-modified asphalt cement) was added.

A substitution on September 14, 1992 replaced an item on rutting susceptibility testing with SMA job mix formula and design limits as indicated in the accompanying sheet.

On October 20, 1992, several significant changes concerning aggregates were made with the addition of Section 802.4, which allowed that aggregate for SMAs could be a combination of fine and coarse aggregate conforming to other standard specification requirements but with three exceptions:

1. Each individual aggregate size had to be Class A aggregate with a Los Angeles abrasion (AASHTO T 96) loss not exceeding 40%.
2. A maximum of 20% flat or elongated particles (on a 3:1 ratio) on material retained on the #4 sieve was allowed.

3. Alluvial gravel and local sand are not allowed in SMAs.

Finally, on July 16, 1993, Section 819 defined the properties required for cellulose fibers, cellulose pellets, and mineral fibers. These are also shown in an accompanying sheet.

33. Serfass, J-P., and Samanos, J.
Stone Mastic Asphalt for Very Thin Wearing Courses, 1992.

This paper deals with the development of SMAs in France. It is one of the few papers that provides the reader with information on the physical characteristics of fiber stabilizers used in SMA.

The authors say that in France the use of SMA for very thin friction courses (about 25 mm in thickness) began in 1983 and developed into the type of SMA that was being used at the date of the paper.

An unusual aspect of the French SMA is the application of a heavy tack coat. The authors warn that while plain asphalt cement can be used for low volume traffic routes, it should not be used in heavy or medium traffic volume situations because of the risks of bleeding. For such heavier traffic conditions, modified bitumen emulsions are used. These are either latex-modified or polymer-modified asphalt emulsions. Application rates vary from 500 g/m^2 on smooth and closed surfaces to 900 g/m^2 on hungry surfaces. [These would appear to result in residual binder thicknesses of about 0.3 mm to 0.6 mm.]

The components of SMA in France are:

AGGREGATES

1. These are high quality, 100% crushed.
2. Maximum size is generally 10 mm.
3. Finer mixes (6 mm down) are sometimes used but mainly in urban areas.

SAND

Manufactured sand is used -- usually about 20% passing the 75µm sieve.

FILLER

Filler is usually of a calcareous nature.

FIBERS

The authors provide a good description of the purpose of fibers in SMA and give the reader some typical characteristics:

Type	Thickness (µm)	Length (mm)	Specific Surface ($cm^2/g\ 10^3$)
Chrysotile	0.1 - 1	0.5 - 1	-
Rockwool	3 - 7	0.25 - 0.75	6 - 7
Glass	5 - 6	Avg. 1	3 - 4
Cellulose	30 - 45	0.3 - 1.5	-

[The above figures give the reader some sense of how small the typical fibers are. At 45µm, the thickest of the cellulose fibers would not be as thick as the average human hair.]

The authors state that various tests can be used to show the effects of fiber addition. One such test is a ring and ball softening point test. [No standard test method is quoted in the paper but presumably ASTM D 36 or AASHTO T 53 would suffice.] The authors include a figure, which displays the different degrees of increase in softening point achieved with increasing fiber content for four different fibers. [The fiber types are not identified.] In another figure, the authors show the gain in unconfined compressive strength of asphalt mixes versus voids in the mixes through the addition of fibers to a 60 - 70 penetration grade asphalt cement. [No details of the mixes are provided and, again, the fiber type is not identified.] The unconfined compressive tests were performed in accordance with an L.C.P.C. method. [The method is not referenced. L.C.P.C. (*Laboratoire Central des Ponts et Chausees)*is the main laboratory of the Ministry of Public works in France.]

ASPHALT CEMENT

1. 60 - 70 penetration grade is normally used.
2. 80 - 100 penetration grade is used in lightly trafficked and cold winter areas.

MIX DESIGN

The main features are:

Maximum size aggregate	10 mm
Gap in grading	between 2 and 6 mm
Crushed aggregate (6 - 10 mm)	65 - 75%
Crushed sand (0 - 2 mm)	20 - 25%
Additional filler and fibers	6 - 10%
Passing 75µm sieve	8 - 12%
Asphalt content	6.3 - 6.8%

The remainder of the paper deals with construction and other aspects of SMA. Among the points of interest are:

1. SMA in very thin layers requires only light rolling. Vibratory and pneumatic-tired rollers are unsuitable.
2. Field impermeability measurements (LPC field permeameter and Saint-Brieuc permeameter) show very good results. The authors attribute the degree of impermeability to the heavy tack coat.
3. Skid resistance measurements using SCRIM (Sideways Coefficient Routine Investigation Machine) at 60 km/h on highways and 100 km/h on motorways and a device used by the L.C.P.C. have been very good.
4. The authors conclude that the overall assessment of SMA with fibers over the preceding eight years has been very favorable.

34. McDaniel, P.
Stone Mastic Asphalt
Missouri's Experimental Project Using European Technology Project Mo. 91-05, 1992.

In this account of Missouri DOT's initial construction of SMA in 1991, McDaniel provides the reader with many details, including searches for suitable materials. The report includes detailed information on placing the SMA on a concrete pavement from which the old asphalt surfacing was previously milled. The following represents some of the main points on mix design, obtained from the report:

MATERIALS

1. A 50/50 mixture of Iron Mountain porphyry and St. Louis limestone was used.
2. Los Angeles Abrasion (AASHTO T96) 35% max.
   Sodium sulfate soundness loss 15% max.
   (AASHTO T 104 -- 5 cycles)

3. The initial source of porphyry yielded flat particle shapes, which were thought to be a direct cause of low air voids. The use of this source was discontinued.
4. An analysis of the limestone mineral filler showed that 48.5% of the material was smaller than 20µm. It was felt that this material may have contributed to low stability values.
5. After placement of the SMA test sections, a marble dust filler from Georgia was tested. This material consisted of less than 10% passing 20µm, but produced similar stabilities to the original mineral filler. [This may again indicate that Marshall stability is not a particularly good indicator to use in SMA mix design.]

The author recommends the gradation of the mineral filler be:

Sieve Size	Percent Passing by Weight
#30	100
#50	95-100
#100	90-100
#200	70-100
#635 (20µm)	0-5

6. Asphalt cement grade -- AC-20.
   Asphalt cement content -- 6.2%, 6.4%, and 6.5%.

Initially, mixes were made with and without SBS copolymers. However, due to limited experience, use of the modifier was stopped to eliminate a confounding factor in the investigation.

STABILIZING ADDITIVES

Cellulose and mineral wool fibers were used. The materials were manufactured in Europe and supplied through distributors in the U.S. In an appendix, the author provides information sheets on the fibers.

In the Missouri SMAs, fibers were incorporated as follows:

Cellulose fibers	0.3% by weight of total mix.
Mineral fibers	8% by weight of asphalt cement.

MIX DESIGN

1. Various gradations were tried before settling on the one shown below. For comparison, the author displays this gradation along with a March 1991 FHWA draft and a German gradation:

	Percent Passing by Weight		
Sieve Size	FHWA	Germany	MHTD
3/4 in.	100	100	100.0
1/2 in.	75	95	96.2
3/8 in.	55	60	75.8
#4	35	35	33.6
#8	22	27	20.0
#16	20	22	14.7
#30	18	20	13.2
#50	15	17	12.6
#100	12	12	11.8
#200	10	8	9.6

2.	Marshall compaction	50 blows.
3.	Air voids, percent	3-4
4.	Flow (1/100 in)	8-15
5.	VMA, percent	16 min.
6.	VFA, percent	78 min.

The Missouri specification for SMA special provisions is included as an appendix. According to this, mix designs for SMAs are performed by Missouri DOT's central laboratory and the job mix formula is provided by the contractor.

The remainder of the report is devoted to construction and sampling aspects of the project.

35. Stuart, K.D.
Stone Mastic Asphalt (SMA) Mixture Design, 1992.

In the first part of his report, Stuart gives a good account of SMA mix design, primarily derived from sources in Sweden and Germany. The second part of the report deals with SMA mix design done by FHWA for Georgia DOT.

At the time of writing the report, Stuart says there is no generic definition for SMA. The gradation is gap-graded but gradations in Europe vary from country to country as do the required minimum binder contents.

Stuart discusses the various components of SMA, dealing extensively with aggregate properties. The following is a summary of the main points made:

AGGREGATES

1. Types

European practice is to use very durable aggregates. For coarse aggregates, granite, basalt, gabbro, diabase, gneiss, porphyry, and quartzite are in common use. The basic qualities sought are a highly cubic shape, rough texture, and resistance to fracturing, polishing, and abrasion. Limestone and sandstone are not used in Sweden or Germany, although crushed limestone filler is often used.

2. Tests

Sweden: Surface abrasion for aggregates and mixtures.
Impact test.
Slotted sieves to determine particle shape.
Germany: Impact test.
Fracture by freezing and heat.
Resistance to expansion or degradation by water.
Particle shape.

The author states that these tests are not used in the U.S. As the LA Abrasion test is not used in Sweden or Germany, there is an element of uncertainty in using criteria from the LA Abrasion test for SMA aggregates in the U.S. However, the author suggests that the 40% value, generally used for open-graded mixes in the U.S., not be exceeded. [No details of the European test methods are given in the report.]

Stuart discusses flat and elongated particles at some length. In Sweden, a slotted sieve method is used to evaluate aggregates above the 4 mm sieve size. The method is not used in the U.S. but the author believes the procedure is worth investigating. In Germany, a length-to-thickness ratio test is performed on aggregates greater than 5 mm. Stockpiles having more than 20% by weight greater than 3:1 are rejected. According to Stuart, the Germans have indicated that some elongated or irregularly shaped particles can improve interlocking and stability although there are no requirements in these respects. Until more is known about the effects of flat and elongated particles in SMAs, the author recommends that a comparable U.S. method, ASTM D 4791, be used on fractions above the #4 sieve with the German criterion of more than 20% by weight greater than 3:1 being grounds for rejection.

Other tests or criteria suggested by Stuart are:

Test/Criteria	Methods	
Clay lumps and friable particles not more than 1%	AASHTO T112	ASTM C 142
Fine aggregates should be non-plastic		
Liquid Limit	AASHTO T89	ASTM D 4318
Plastic Limit and Plasticity Index	AASHTO T96	ASTM D 4318
Sand equivalent 45 min. On minus #4 sieve material	AASHTO T176	ASTM D 2419
Sulfate Soundness loss (sodium) - 5 cycles 15% max. (magnesium) - 5 cycles 20% max.	AASHTO T104	ASTM C 88

BITUMEN

Stuart notes that the grades used in Europe are generally 65, 80, or 85 penetration from consistent sources. Sweden, for example, uses only Venezuelan crudes. A 200 penetration grade is also used in Germany for thin lifts with maximum aggregate size of 5 mm. The author concludes that highway agencies in the U.S. should be able to use their customary grades.

STABILIZING ADDITIVES

The fibers commonly used are cellulose and rock wool. In Sweden, the volume usage of both is about equal but in Germany, it is about 95% cellulose. Most of the rock wool is manufactured in Sweden. Norway uses rock wool while Denmark and the Netherlands use cellulose. The author notes that there are no generic specifications for fibers although manufacturers have specifications for the products that they market. While there are many types of cellulose fiber, Stuart makes an interesting observation that specific types have been developed 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. Adherence of asphalt to cellulose is often low without coatings and/or the fibers swelling."

Stuart says that various polymers have been used in some European countries to stabilize mixtures. Combinations of polymers with fibers have also been done but only on a limited basis in

Sweden and Germany. The author says that several sources in Europe think the combination of fibers and polymers may provide the best SMA properties but cites high costs and lack of supportive data.

Typical dosage rates for cellulose are from 0.3 to 0.6% by weight of mix with 0.3% being common. Rock wool dosage is slightly higher. SMAs with nominal maximum size aggregate at the #4 sieve level may need only 0.15% fiber. Polymer content is generally in the range 5 to 8% by weight of asphalt cement. In Sweden and Germany, drainage tests are used to determine the amount of stabilizer required. Details of the German drainage test, commonly known as the Schellenberg Test, are given in Stuart's report.

MIX DESIGN

[The German specification is reviewed in Reference 10. The reader may find it convenient to refer to the table in that review.]

According to Stuart, automatic Marshall hammers are generally used for compaction at a 50-blow effort. Laboratory compaction temperatures are:

Sweden	145 - 150°C	(rarely more than 155°C but up to 170°C is allowed when fibers are used).
Germany	135°C.	

Neither loose nor compacted mixtures are oven-cured in either country.

There are no VMA or VFA requirements but when measured, according to Stuart, these properties are generally above 16.5% and 78%, respectively, for a nominal maximum size aggregate of 12.5 mm.

Stuart notes that the German specification was developed using cellulose fibers. Other stabilizers generally do not hold as much bitumen as cellulose fibers; their use nearly always results in lower binder contents that often do not meet the German specification. However, Stuart notes that the reasons for claiming cellulose fibers allow higher binder contents to be incorporated in SMAs compared with other fibers are not known but he recommends they should be determined. [See also Reference 76.]

According to Stuart, Marshall stability and flow criteria for dense-graded HMAs can be used for SMAs. However, stability traces do not have well-defined peaks. In Europe, stability and flow values are often not used, many designs being based on air void requirements and minimum binder content. The author includes a table of proposed gradations for several nominal size aggregates for SMAs in the U.S. Stuart recommends that the gradation be near the lower end of the #8 sieve as he believes this will give a high stone-on-stone contact, high VMA, and allow for a high binder content.

Stuart conjectures that some raveling problems experienced with SMAs may be due to moisture susceptibility among other potential causes. He recommends moisture susceptibility testing be included in evaluating SMA mixes designed in the laboratory. Test methods are ASTM D 4867 or

AASHTO T 283. However, these tests are commonly done at air void levels between 6 and 8% and an applicable range for SMAs, which compact readily in the field to 3 or 4%, is not known. Until this uncertainty is resolved, Stuart recommends a range of 5 to 6% be used.

The author reports that very little in the way of strength tests has been done on SMAs in Europe. He says that it is yet to be determined if diametral modulus and tensile strength tests are applicable to SMAs. At the time of writing the report, Stuart indicated that research was underway in Germany and the Netherlands on the resistance of SMA mixtures to permanent deformation using creep, repeated load, and wheel-tracking tests. [At the time of writing this review, no reports on these endeavors had been received.]

The second part of Stuart's report provides much detail on the materials analyses and mix designs for coarse-graded and fine-graded SMAs, which were placed on the I-85 in Georgia in 1991. A 50-blow Marshall design was used. The optimum binder content was taken at 3.5% air voids level at Georgia DOT's request. Georgia DOT highway agency also required the binder content to be between 5.5 and 7.5% by weight of mixture, a minimum Marshall stability of 1500 pounds, a flow between 5 and 16 (1/100 in.), and VFA between 65 and 85%. Stuart points out that the optimum binder contents obtained were in the range desired by the highway agency but were lower than those generally used in Europe. However, at 3% design air void level, he noted that the binder contents of the three mixes investigated would be close to the recommended level of 6% given in the first part of his report.

The Schellenberg Test was performed at an elevated temperature (163°C) on the coarse-graded SMA, which easily passed the test.

Length to thickness tests at ratios of 3:1 and 5:1 were performed on all three aggregates. Georgia DOT allows a maximum of 10% by weight using the 5:1 ratio, which the author says is a very lenient specification. All three aggregates easily passed the Georgia DOT requirement but failed the German limit of 20% by weight using the 3:1 ratio.

In accordance with Georgia DOT standard practice, hydrated lime at 1% by weight of aggregate was included as an anti-stripping agent. Stuart reports that all three mixes passed the Georgia DOT moisture susceptibility test, which is based on AASHTO T 283. The tests were done by Georgia DOT.

36. *Splittmastixasphalt*, 1992.

This is a guideline booklet, developed by the German Asphalt Pavement Association. [At the time of review, a translation into English was underway but had not been completed for general release.]

The booklet is based on Part 4 of the "German Technical Specifications and Guidelines for the Construction of Asphalt Pavements" [Reference 10]. After informing the reader on how SMA came to be developed to resist studded tire wear, the booklet explains why the German SMA specifications have minimum asphalt cement contents. After SMA was brought into the standard German specifications, mixes were often produced at the minimum borderline specification of 6.0% asphalt cement content. Variations in production led to a series of deficiencies, which in turn led to the 1990 revision of the specification and the minimum 6.5% asphalt cement requirement.

The German Highway and Transportation Research Association recommends a minimum asphalt cement content of 6.8% by weight of mix for mix design and JMF. According to the booklet, such high asphalt cement contents have been achievable only with fibers so far. The authors of the booklet [a committee] believe that acceptable SMAs can be produced using the standard German specification [Reference 10]. A table showing the main requirements of the standard specification along with the recommendations of the Highway and Transportation Research Association is included in the booklet. Mineral aggregates are designated to be double crushed premium quality aggregate, manufactured sand and/or natural sand, and mineral filler. An adaptation of the table is shown below.

Splittmastixasphalt	0/11S**	0/8S** 0/8	0/5
Sieve Size	Percent Passing		
11mm	≥ 90	100	100
8mm	≤ 75 (≤ 65)*	≤ 90	100
5mm	30 - 50 (30 - 45)*	30 - 50	90
2mm	20 - 30	20 - 30	30 - 40
90µm	8 - 13 (10 - 13)*	8 - 13 (10 - 13)*	8 - 13 (10 - 13)*

* Recommendations of the Highway and Transportation Research Association
**S is for *schwer*, meaning heavy. These gradations are intended for heavily trafficked pavements.

According to the booklet, the primary characteristics of SMA are:

1. A high content of double crushed coarse aggregate.
2. A high proportion of coarse aggregate, i.e., a gap-graded mix.
3. A high asphalt cement and mortar content.
4. The use of a stabilizing additive.

The authors make the point that stabilizing additives prevent segregation and drainoff as well as providing thick asphalt films, which mitigate against aging.

For highway maintenance, the authors believe 5 or 8 mm top size SMA is well suited.

The booklet offers some advice on materials and mix design. [No tests for aggregates are mentioned.] Asphalt cement grades are usually 65 or 80 penetration. For thin surfacings, 200 penetration can be used. In some cases where very thin layers are required (e.g., bridge decks) a polymer-modified asphalt cement may be advantageous. Marshall specimens are prepared in accordance with German test standard DIN 1996, Part 4 at 135°C ± 5°C. [The booklet does not mention the number of blows of compaction but presumably it is intended to be 50 blows per side.] The target voids content is 3%. However, for thin overlays of SMA, the target voids level is reduced to between 2 and 2.5%, depending on traffic. The booklet cautions against attempting to control the void content in SMA design through altering the asphalt cement content. Higher voids can be obtained through:

1. Altering the total coarse aggregate and the proportions of the individual gradations.
2. Changing the filler content and/or type.
3. Altering the asphalt cement content only as a last resort.

A series of diagrams comparing Marshall properties for SMA and dense-graded HMA is provided. The text warns the reader that comparing the Marshall properties of the two mixes is of little value and can lead to incorrect conclusions about the performance of SMA.

The remainder of the booklet deals with SMA production, placement, and compaction. Some good practical advice is offered in this part of the booklet. The information can be summarized as follows:

1. Two cold feed bins for the largest size of aggregate are recommended.
2. A reduced amount of sand in SMA compared with other mixes means that attention needs to be paid to production temperature. The higher proportion of coarse aggregate will heat more rapidly without the screening effect of the sand. The mix temperature should not exceed 180°C for regular SMA and should not be more than 160°C when 200 penetration grade asphalt cement is used.
3. Protect organic fibers from moisture and clumping.
4. Distribute fibers uniformly. In a cut-away drawing, the booklet shows apparatus for proportioning powdered and pelletized additives.
5. Required dry and wet mix cycle times can cause a decrease in production capacity.
6. Keep storage time in silos as short as possible to minimize drain off.
7. Cover loaded trucks to prevent cooling.
8. Overheating SMA to compensate for cooling during long hauls to the paving site can cause drain off, harden the asphalt binder and lead to poor placement and compaction efforts.
9. Mix temperature in the paver hopper should not exceed 150°C for SMAs with 65 or 80 penetration grade asphalt cement or 140°C for 200 penetration grade.
10. Set the paver screed on maximum compaction and adjust the paver speed accordingly.
11. Start compaction as soon as possible. If operating a vibratory roller and asphalt cement and fines are brought to the surface, cease rolling immediately.

12. Use a minimum of two steel-wheeled rollers per lane. Static heavy tandem or three-wheelers greater than 10 tons are preferred.
13. Use vibratory rolling only if the mix temperature is sufficiently high and only following a static roller.
15. Do not use vibratory rolling if the layer is less than 20 mm or if there is a hard subsurface.
16. Exercise caution if pneumatic-tired rollers are used.
17. A skid-resistant aggregate may be applied directly behind the paver and after the first roller pass has been made. Typical materials used are:
    Dust-free fine crushed aggregate at 1 to 2 kg/m².
    Dustless or lightly coated crushed sand (0.25-2.0 mm).
    Manufactured and natural sand.
18. Pneumatic-tired rollers can be used in conjunction with the application of the skid-resistant aggregate.
19. The Schellenberger Drainage Test is described in an appendix.

37. Prendergast, J.
A European Road Comes to the U.S., 1992.

This news item covers, among other things, the growth in interest in SMA in the U.S. following the European Asphalt Study Tour. The author gives a brief description of the essential features of SMA and reports comments by state, federal, and contractors' representatives. The author also reports briefly on the 1991 SMA demonstration projects in Michigan, Georgia, and Missouri.

38. Matteson, J.E./Kuennen, T.
Did Phoenix Originate SMA Mix Design? 1992.

This article, edited by Kuennen from material provided by Matteson, poses a claim that SMA mixes are little more than a variation of open-graded asphalt rubber hot mix, developed in Phoenix more than 25 years ago and used by the Arizona DOT. The contention is that recent changes have brought about a gap in the grading of asphalt rubber mixes that allows a much higher percentage of asphalt rubber binder in the mix. A gradation chart for a 1/2-inch nominal size aggregate is included. [The gradation shows between 3 and 9% passing the 75µm sieve, which is lower than that typically used in SMA.]

39. Milo, A.C.
New Mixes, Modifiers Put to Test on I-94, 1992.

In this technical news item, Milo reports on a Michigan DOT experimental research project on I-94. The objective was to compare the performance of SMA with a Michigan DOT high performance 4C mix. The leveling course over the entire project was a new large-stone Michigan 2C mix. The 14-mile project included sections of polymer-modified SMA over unmodified and polymer-modified 2C; SMA with cellulose fibers over unmodified 2C and 2C with cellulose fibers; and three sections of polymer-modified 4C, 4C with cellulose, and unmodified 4C over an unmodified 2C leveling course.

The author includes the composition of various Michigan DOT mixes, including the aforementioned 2C and 4C mixes, and the SMAs. Three SMAs are shown with identical gradations but the SMA-C [cellulose] shows a 1% higher range for bitumen than SMA-P [polymer] and SMA-M [mineral wool]. Milo reports that because of supply difficulties, mineral wool was not used in the project.

[No other mix design information is provided in the article.]

40. Brown, E.R.
Experience with Stone Matrix Asphalt in the United States, 1992.

In 1991, the first five major SMA projects were constructed in the U.S. These were in Georgia, Indiana, Michigan, Missouri, and Michigan. Dealing with these projects in chronological order, Brown provides some mix design and construction control data. However, Brown's report is primarily from the construction perspective. The main points of interest from a reading of the report are as follows:

WISCONSIN SMA

1. Mix design by Wisconsin DOT. Wisconsin DOT's specification for SMA is included as an appendix.
2. 50-blow Marshall compaction with slanted foot and rotating base Marshall hammer.
3. Air voids 3.1%.
4. Polymer additive used as a stabilizer.
5. Optimum asphalt cement content 5.7%.
6. Asphalt cement grade 85 - 100 penetration.
7. Polymer 7% by weight of asphalt cement.
8. LA Abrasion (AASHTO T 96) 45% max.
9. Sodium sulfate soundness loss (AASHTO T 104) 5 cycles 12% max.
10. Brown notes that the compactive tool used has been shown to produce higher densities than the standard automatic Marshall hammer with a fixed base. He cites the use of this hammer along with the use of a polymer instead of fibers as a stabilizing additive as possible reasons for the relatively low optimum asphalt cement content.
11. Fractured faces on particles above the #4 sieve:
    One fractured face 90% min.
    Two fractured faces 60% min.
12. Marshall stability 1500 pounds min.

13. VMA 15 min.
14. PI of filler (passing #200 sieve portion) $\ngtr$ 3.

Brown shows the mix design and plant-produced mix gradations being in very close agreement. [They both meet the German specification as proposed by Stuart in Reference 35.]

GEORGIA SMA

SMA sections were placed on the I-85 in the summer of 1991 in Georgia. NCAT developed a preliminary mix design for Georgia DOT for comparison with mix designs by others [see References 16 and 35]. Brown reports that all mix designs produced results similar to that ultimately used by Georgia DOT. The report includes these mix design properties and also mix production properties in two tables. Brown notes some minor differences between the design and produced properties. Changes were made in asphalt cement and fiber contents during production primarily to evaluate the effects on mix performance. He also cites some differences in plant-produced gradation compared with design intentions. [NCAT's preliminary mix design work is not reported.]

MICHIGAN SMA

Brown reports that the mix design was developed by Michigan DOT. [The mix design method is not stated.] In an appendix, the author includes the Michigan DOT special provision for SMA. The special provisions include:

1. Filler -- PI $\ngtr$ 4.
   Retained on #100 sieve $\ngtr$ 4%
   Retained on #200 sieve $\ngtr$ 15%

The author includes a table showing mix design and plant-produced properties of the SMA. Drum and batch mixers were used. [The intended gradation meets the German gradation for ½ in. SMA as suggested by Stuart in Reference 35.] Brown's comments in the remainder of this portion of the report pertain to his observations on construction aspects. However, he notes that the mix produced in the field was considerably finer on several sieves than the mix design. This resulted in the VMA of laboratory-compacted samples of the produced SMA being about 2% lower than the design VMA. This caused the asphalt cement to be lowered.

MISSOURI SMA

The mix design was done by Missouri DOT. Brown includes mix design and construction data in a table and provides some construction arrangements between Missouri DOT and the paving contractor in an appendix. The mix design data show both cellulose and mineral fiber contents of 0.3% of total mix. For the plant-produced SMAs, Brown shows the cellulose content at 0.3% and the mineral wool fiber at 0.5% of total mix. The author states that the batch plant-produced mix was slightly finer than the designed mix but the differences in gradation were not significant. Brown notes that when fibers were added to the pugmill before the aggregate, some balling of fibers was experienced. Adding fibers after aggregates were in the pugmill resulted in good distribution of the fibers.

INDIANA SMA

Brown reports that the Indiana SMA, placed on I-70 in 1991, was unusual in that there were no fibers but that a multi-grade asphalt cement (designated MG 20-40) was used in the matrix. Design asphalt cement content was 6.5%. Aggregates were 100% crushed but the gradation was different from other SMAs observed by the author. The other four projects, says Brown, had approximately 70 to 80% passing the ⅜ inch sieve whereas the Indiana mix had 31% passing this sieve. [The gradation at this sieve would also be slightly outside the German specification suggested by Stuart in Reference 35.]

Included as an appendix is Indiana DOT's special provisions for SMA. This contains the characteristics required for the MG 20-30 and indicates that the contractor is responsible for the job mix formula and mix design. It indicates too that the aggregates required are dolomite coarse aggregate, dolomite sand and mineral filler, the last mentioned being derived from dust produced by crushing stone. Carbonate rock containing at least 10.3% elemental magnesium (Indiana Test Method 205) is the source material.

Brown concludes his report with a summary of his observations on the SMAs produced up to the time of his report. The main points include:

1. 100% crushed aggregates.
2. No natural sands.
3. LA Abrasion usually in the range 20 - 30.
4. Common gradation features for all the SMAs are:

Sieve Size	Percent Passing
1/2 in.	94 - 100
#4	28 - 37
#50	12 - 14
#200	8 - 11

5. Asphalt cement grades used have been AC-20, AC-30, 85-100 penetration, and MG 20-30.
6. Cellulose fiber at 0.3% of total mix, mineral fiber at 7 to 8% of asphalt cement. Fibers in pellet form in one project did not break down completely.
7. All mix designs used 50-blow Marshall compaction.
8. Pneumatic-tired rollers should not be used.
9. Initial in-place voids have typically been in the range of 5 to 7%.
10. Skid resistance qualities appear to be good. Applying fine chips to the hot SMA, as is sometimes done in Europe, does not seem to be required although some flushing occurred in one project.

41. Bellin, P.
Use of Stone Mastic Asphalt in Germany
State-of-the-Art, 1992

Bellin reviews the development of SMA in Germany from the 1960s when special asphalt mixes were sought to resist the extreme wear of asphalt surface courses due to the use of studded tires. SMAs were first developed under proprietary names by a few large companies. Mixes became standardized in 1984 and the specification was revised in 1990. [See Reference 10.]

The author, who is an engineer in Lower Saxony, gives a practicing engineer's perspective in reviewing the German specification. In Germany, every bidder can submit alternative or innovative proposals. This stimulates contractor-led investigations, research, and development of improved technology.

Bellin explains some requirements of SMA, with reference to the German specification:

AGGREGATES

Premium quality aggregates are double crushed, and specific in size, soundness and shape. Flat and elongated stones are limited to 20%. All aggregates, sand, and filler are under independent third party quality assurance.

Mineral types are not named in the specification but are regularly specified in requests for proposals. Limestone, sandstone, and "soft" aggregates are not used. Minerals of choice are gabbro (traprock), diabase, basalt, and granite.
Also, good resistance to polishing is required.

The type of sand is not specified but at least 50% of the sand fraction must be crushed.

FILLER

The type of filler is not named in the specification or in requests for proposals. Ground limestone is used in mixes but baghouse fines are not used much.

GRADATION

Bellin provides a gradation chart in which a typical dense graded HMA is compared with an 11 mm top size SMA that meets the German specification.

ASPHALT CEMENT

For regular traffic, 80 penetration is used.
For heavy traffic, 65 penetration is used.

STABILIZING ADDITIVES

The specification allows the use of organic and mineral fibers, granulated or pulverized polymers, or siliceous acid (silica).

The contractor is responsible and accountable for the selection of the appropriate additive and its content in the mix.

According to Bellin's experience, a stabilizing additive is necessary for the mastic part of the SMA. Polymer-modified bitumens alone are not sufficient.

In Germany, stabilizing additive usage in SMAs is dominated by cellulose fibers:

Cellulose fibers	80%+
Mineral fibers	5%-
Polymers	10%-
Siliceous acid	5%-

As all the above are permitted equally and without differentiation in SMA requests for proposals and specifications, the predominance of cellulose appears to be a result of contractors' preference. [This seems to be a significant point.] The contractor is not only responsible for the choice of stabilizing additive but also for guaranteeing that the work is fit for the intended use, without latent defects, for up to four years. The burden of proof is on the contractor that the executed work is in accordance with the contract although the client has the burden of proof in cases of latent defects and premature distress.

RAP

Reclaimed asphalt pavement (RAP) has not been evaluated and, therefore, is not used in SMA. Bellin expresses concern about cold milling and mixing in recycling operations with polymer-modified asphalts. He cites problems with "... spinning endless thin rubber threads ..." and apprehension over chemical reaction and health hazards.

MIX DESIGN

A unique aspect of the German specification is that there is no specific design method. Bellin says the following steps are taken in evaluating an appropriate job mix formula (JMF).

1. A trial gradation, based on previous experience and in accordance with the specification limits, is chosen.
2. Trial mixes are prepared at the lowest required asphalt cement content and at several other contents.
3. A bitumen drainage test, which is not [in 1992] standardized or required in Germany, is used to determine the type and content of the stabilizing additive. The author says the test was

developed and is performed by the Schellenberg Laboratory, Rottweil/Baden-Wurtemberg, Germany. Bellin provides a description of the test.

4. Marshall specimens [no compactive effort stated by the author] are compacted at 135 °C and the air voids content calculated. The value must be between 2 and 4%. If the air voids content is outside this range, the following steps in order of priority are taken:
   (1) Change the content of single sizes or the total content of crushed coarse aggregates.
   (2) Change content and/or type of filler.
   (3) Change content and/or type of stabilizing additive.
   (4) Change the asphalt mortar content.

Bellin emphasizes that Marshall stability and flow are not adequate for evaluating SMAs and are not used for that purpose.

The remainder of Bellin's paper deals with some aspects of production, placement, and compaction of SMAs. He cautions against the use of vibratory compaction and says it is not advisable with layers about 20 mm thick and at temperatures under 100 °C. He is also cautious about the use of pneumatic-tired rollers. Because of the high asphalt contents of SMAs, there is potential for a binder-rich surface or flushing, resulting in initial low skid resistance. To counter this, Bellin says a surface treatment is recommended. This is the application of fine crushed aggregates (free from dust) in the range 0.7 to 3 mm, spread at 600 to 900 gms per square metre. This is done after the first roller pass.

42. Bukowski, J.R.
The Future of SMA in America, 1992.

In this informational article, Bukowski reports that the first five SMA projects in U.S., constructed in the summer of 1991 in Georgia, Indiana, Michigan, Missouri, and Wisconsin, are performing well under traffic. Among the preliminary findings, which were made following evaluations of these SMA projects, were:

1. The amount of material passing the #4 sieve should be 30% or less.
2. The portion of the mineral dust less than 0.02 mm in size should be no more than 3% of the total aggregate.
3. No more than 20% of the coarse aggregate should have a length to width ratio of 3:1 or greater.

The author includes a chart of completed SMA projects in 1992. This shows nine projects in eight states (Maryland had two). Drum mixers were used on seven projects and batch mixers on two. Stabilizing additives varied from cellulose and mineral fibers, to cellulose pellets, elastomers, and polyolefin.

Bukowski believes that SMAs should continue to follow the "30-20-10 rule" (30% passing the #4 sieve, 20% passing the #8 sieve, and 10% passing the #200 sieve) for 1/2-inch top size aggregate mixes.

The author indicates that laboratory compaction methods are being evaluated. He reports that in current SMA projects, 50-blow Marshall was used as practiced in Europe. Bukowski noted that other compaction devices, such as the gyratory procedure, produce lower air voids. [The author does not say at what level of gyratory compaction such comparisons are made.]

43. Schütz, O.W.
Construction Procedures for Asphalt Concrete Pavements in Europe, 1992.

As the title implies, this paper is concerned mostly with construction procedures. SMAs are, however, mentioned in several parts of the text by Schütz, who is a German contractor. A few points can be obtained from the paper:

FILLER

1. Mineral filler is defined as material passing the 90µm sieve.
2. SMAs require 8 to 13% mineral filler.

ADDITIVES

1. Commonly used additives are organic fibers, mineral fibers, and polymers.
2. Because additives are regularly used, they are often held in storage silos and fed to the pugmill as needed. [There are few, if any, drum mix plants in Germany.] For plants that do not produce much SMA, the additives are introduced into the pugmill in meltable plastic bags, the content of the bag being proportioned to the capacity of the pugmill.

MIXING

1. When organic fibers are used, the dry mix cycle is extended by 5 to 10 seconds.
2. With powdered or granular polymers in SMAs, no additional dry mix time is usually needed.

RELEASE AGENT

Truck beds must be clean and coated with a release agent of soapy water. The author stresses these aspects for high binder content mixes, such as SMA, and for all polymer-modified mixes.

COMPACTION

Vibratory rolling is not used for compaction of SMA because of the risk of fracturing the aggregate.

44. Van der Heide, J.P.H.
Materials and Mix Design, 1992

The author, who is employed by the Netherlands Asphalt Pavement Association, provides some startling facts in the background information with which he begins his paper. According to the table provided, the figures appear to show that Finland was the biggest producer of SMA in terms of tonnage in Europe in 1990. Switzerland was second with a production slightly more than Germany and almost three times as much as Sweden. [Switzerland uses the German specification for SMA.]

In the SMA section of his paper, the author explains the concept of SMA. By means of a chart he shows the development of voids when a sand, which itself has a voids content of nearly 30%, is mixed in varying proportions with a coarse aggregate ($\succ$ 2 mm).

The author says that the skeleton of SMA consists of about 85% coarse aggregate and 15% fine aggregate, giving voids in the composite structure in the range 30 to 35%. This void area in the composite skeleton is almost filled with a mastic, which the author calls a "Gussasphalt", an overfilled mixture of binder, filler, and sand. The remaining void content in the mix is about 4 to 6%.

SMA design is not specifically addressed but the author provides a list of coarse aggregate and sand specifications that are mentioned in the draft of a new European specification. In this list, the LA Abrasion Test is said to be preferred.

The author notes that in Germany, a new Marshall apparatus with a steel anvil has been developed.

45. Harrigan, E.T.
Transfer of Technology from Europe to the USA, 1992.

This is a record of the discussions that followed an unpublished presentation by Harrigan. Much of the discussion related to costs of SMA, which various participants put at from 20% to 50% or more of the cost of typical dense-graded mixes. However, one discussor points out that up to the present time, most SMA projects in the U.S. had been small test sections.

On thickness of layers, Harrigan said the thicknesses of SMAs that he saw in Europe were typically about 40 mm.

46. Scherocman, J.A.
Construction of Stone Mastic Asphalt Test Sections in the U.S., 1992.

In this paper, the author begins with his account of SMA mix design, which seems to be derived from European sources. The main points made are:

AGGREGATE

1. Gradation is essentially gap graded.
2. Top size aggregate varies from ¼ in. to 1 in., with the most commonly used in Europe being 5 mm, 8 mm, or 11 mm.
3. For fine-graded SMA surface courses -- 34 to 40% passing the #4 sieve.
   For coarse-graded and binder courses -- 28 to 34% passing the #4 sieve.
   For both fine and coarse SMAs -- 8 to 13% passing the #200 sieve.
4. Low LA Abrasion loss. [No value is suggested.]
5. Cubical aggregate shape, without any significant amount of flat or elongated particles. [No criteria given.]
6. Baghouse fines are not normally fed back into SMA mix production in Europe.

ASPHALT CEMENT

1. Polymer-modified SMA, asphalt cement content -- 5 to 6.5%.
2. SMAs with organic or mineral fibers -- 5.5 to 7%.
3. German SMA mix designs require the minimum asphalt cement content to be 6.5%. Asphalt cement contents in north American SMAs have been significantly lower.
4. Penetration grades of asphalt cement have been used in European and Canadian SMAs. In the U.S., both penetration and viscosity grades have been used.

MIX DESIGN

1. 50-blow Marshall compaction per side is used.
2. Marshall stability and flow values are measured.
3. Air voids and VMA are calculated.
4. Optimum asphalt cement content is usually chosen at 3% air void. At this level, stability, flow, and VMA are compared with minimum required values in the specifications.
5. Fibers are typically included at 0.3% by weight of aggregate.
   Polymers may be incorporated at 3 to 8% by weight of asphalt cement.

Scherocman then reviews five SMA projects from which the following points are noted:

ONTARIO

1. Markham project
   Glass fibers were added to both the binder and surface courses at 0.3% by weight of aggregate. The mineral filler for the surface course was 5% fly ash.
2. Highway 7 project
   Glass fibers were also added in this project at 0.3% by weight of aggregate. The binder was a polymer-modified asphalt cement and the binder content was 5.3%.
3. Highway 404 ramps
   Three test sections were constructed here, using a polymer-modified 60 - 70 penetration asphalt cement at 5.1% design content; the same polymer-modified 60 - 70 grade at 5.6% but with cellulose fibers added at 0.3% by weight of aggregate; and a section designed at 4.9% 85 - 100 penetration grade asphalt cement, which was modified with 7% of the polyolefin to give an effective asphalt content of about 5.3%.

The filler was 8% limestone dust and the passing #200 sieve was 10.7%.

[Considerable details on the above three projects are provided by Kennepohl and Davidson (Reference 47).]

The author provides some information also on the 1991 SMA projects in Wisconsin, Georgia, Michigan, and Missouri.

Scherocman expresses concerns about differences between SMA design in Europe compared with the U.S. In particular, he mentions the high quality of aggregates used in Europe, the number of flat and elongated particles that can be used, the degree of aggregate faces crushed, the type, nature and gradation of filler (passing 75µm sieve), and the amount and gradation of baghouse fines that are returned to the mix.

47. Kennepohl, G.H., and Davidson, J.K.
    Introduction of Stone Mastic Asphalts (SMA) in Ontario, 1992.

The authors begin their paper by providing the reader with an understanding of the concept and key features of SMA. They then go on to present the results of SMA mix designs for three projects, which were constructed in Ontario between December 1990 and October 1991. Job mix formulae, mix proportions, and Marshall properties are presented for all three projects. [These projects were described also by Scherocman (Reference 46) but not with the detailed data presented by Kennepohl and Davidson.] Points noted are:

MARKHAM PROJECT

1. Compactive effort was 75-blow Marshall because of fears that the SMA would densify under expected heavy traffic. [In later projects, 50-blow Marshall was used.]

2. Asphalt cement grade 85 - 100 pen.
3. Compaction temperature in laboratory:
   Surface mix (6.5% asphalt cement) 150°C
   Base course mix (5.5% asphalt cement) 145°C
4. Filler type (5% of aggregate) Fly ash
5. Aggregates were limestone, traprock, and limestone screenings. [In the discussion to the paper, Kennepohl says LA Abrasion tests were done. However, no aggregate test data are given for any of the projects.]
6. Fiber type (0.3%) Glass fibers
   [It is not clear from the paper if the fiber content is by weight of mix or by weight of aggregate. It appears to be by weight of mix.]
7. VMA surface mix 19.0%
   VMA base course mix 15.6%
8. Air voids surface course 3.36%
   Air voids base course mix 2.69%
9. The gradations of both mixes are reasonably close to the gradations suggested by Stuart (Reference 35) except that they are noticeably finer at the ⅜-inch sieve and are slightly low at the #200 sieve.

HIGHWAY #7 PROJECT

This was a surface course only.

1. Compactive effort was 37-blows mechanical on each face (rotating base and beveled foot).
2. Asphalt cement grade (polymer modified) 60 - 70 pen.
3. Compaction temperature in laboratory 135°C
4. Filler type (8%) Ground dolomite
5. Aggregates were dolomite sandstone and dolomite screenings.
6. Fiber type (0.3%) Glass fibers
7. VMA 15.8%
8. Air voids 4%
9. The gradation meets both the German and Swedish specification grades that Stuart (Reference 35) suggests except at the ⅜-inch sieve where it is noticeably finer. The passing #200 sieve was 10.8%.

HIGHWAY #404

Three SMA mix designs were done: Polymer-modified 60 - 70 penetration grade asphalt cement with and without cellulose fibers, and a polyolefin-modified 85 - 100 penetration grade asphalt cement without fibers. Mix designs were also done independently by a German contractor. The results of both designs are presented and show close agreement with each other.

1. Compactive effort was 37-blows mechanical on each face (rotating base and beveled foot).
2. Compaction temperature in laboratory - 135°C.

3. Filler type -- limestone.
4. Aggregates were traprock and Dufferin sand.
5. Fiber type (0.3%) - cellulose.
6. Other properties:

	Asphalt Cement Content	VMA	Voids
(Polymer + fiber mix)	5.6%	15.8%	3.0%
(Polymer only mix)	5.1%	15.1%	3.2%
(Polyolefin only mix)	4.9%	14.4%	3.0%

The remainder of this paper deals with production and construction aspects of the SMA for the three projects, and the results of field test data. Low voids were found on the Markham project from which slabs were removed for rutting tests, using the Ministry of Transportation wheel tracking machine. On the basis of this test, the SMA surfacing and base courses demonstrated significantly better rutting resistance compared with the control section of asphalt concrete.

48. Brown, E.R.
Evaluation of SMA Used in Michigan (1991), 1992.

In a previous report (Reference 40), Brown provides some information on SMA that was placed in Michigan in the summer of 1991, one of the first SMAs to be placed in the U.S. The author notes that there had been very little testing of SMAs in the U.S., with the consequent difficulty of selecting the optimum asphalt cement content. A study was undertaken to evaluate the sensitivity of SMA mixture properties to changes in the proportions of several ingredients. The laboratory research work was performed with the same materials and job mix formula that were used in the Michigan project. For comparison purposes, a dense-graded HMA using the same aggregate and job mix formula was prepared and tested.

The mix components that were varied were:

1. Cellulose.
2. Asphalt cement content.
3. Percent passing the #4 sieve.
4. Percent passing the #200 sieve.

The tests and measurements performed to evaluate the changes were:

1. Tensile strength.
2. Marshall stability and flow.
3. Gyratory Stability Index (GSI).
4. Gyratory Elastic Plastic Index (GEPI).
5. Gyratory Shear Stress to produce one degree angle.
6. Resilient Modulus.

7. Confined Creep.
8. Voids, VMA, and voids filled.

FINDINGS

Brown acknowledges that this was a limited study, using one aggregate, one asphalt cement, and one stabilizing fiber. The author cautions that care should be exercised in using the results to make general statements about SMA. The conclusions were:

1. SMA performed reasonably well in the Confined Creep test and generally performed better than the dense-graded HMA in the procedure for the Gyratory Shear Stress to produce one degree angle. Brown notes that these two tests are indicators of rutting resistance.
2. The SMA mixtures had much lower tensile strength values (indirect tensile strength and resilient modulus) than the dense-graded HMA. However, Brown notes that the lower tensile strength properties should not affect the properties of SMA.
3. Aggregate gradation significantly affects the performance of SMA in laboratory testing.
4. The addition of fiber had little effect on VMA and the optimum asphalt content.
5. Lowering the percent passing the #4 sieve is the best way to increase the optimum asphalt content. Lowering the filler content will accomplish the same effect but result in asphalt binder drainage problems.
6. Tests that are more related to performance are needed to evaluate SMA mixtures. Creep and Gyratory tests appear to be the most promising.

49. Scherocman, J.A., and Schütz, O.W.
The Construction and Performance of Polymer Modified Asphalt Concrete Pavements, 1992.

Scherocman and Schütz note the increased use of polymer-modified asphalt concrete mixes in the U.S. in recent years and the introduction of SMA into the North American asphalt scene. The authors describe the mix designs used for three polymer-modified HMAs -- a large stone mix in Kentucky, three SMAs in Frankfort, Germany, and the SMA on I-94 in Wisconsin in 1991. [The large stone mix in Kentucky was not an SMA and is not reviewed here.]

GERMANY

AGGREGATES

For the work in Germany, the authors state that six different aggregates were blended. The types and proportions were:

Aggregate Type	Size mm	Amount Percent
Diabase	11-16	34.0
Granite	8-11	18.0
Diabase	5-8	15.0
Basalt	2-5	6.0
Basalt Sand	0-2	16.0
Limestone Dust	0-0.09	11.0

The gradation for all three mixes was:

Sieve Size		Percent
mm	U.S.	Passing
22.40	7/8 in.	100.0
16.00	5/8 in.	98.3
11.20	1/2 in.	68.7
8.00	3/8 in.	51.3
5.00	#4	35.8
2.00	#10	26.4
0.71	#25	19.6
0.25	#60	15.6
0.09	#170	12.3

[The gradation appears to be close to the gradation for ¾ inch top size material suggested by Stuart (Reference 35).]

A control mix without additive was prepared for comparison purposes but was not constructed. Among the mix design properties for the mixes were:

Mix Property	Control Mix	Polyolefin Fiber	Mineral Fiber	Organic Fiber
Air Voids %	2.9	2.8	2.9	3.2
VMA %	16.1	17.0	17.4	18.3
VFA %	81.9	83.5	83.3	82.5
Asphalt Content %	5.3	5.6	5.9	6.2
Indirect Tensile Strain (40°C, N/cm²)	32.8	39.2	29.1	31.7
Indirect Tensile Strain (25°C, N/cm²)	78.8	83.2	77.1	67.6

The authors point out the superior indirect tensile strength of the polyolefin-modified mix. [However, as noted by Brown (Reference 48), lower tensile strength properties should not affect the properties of SMA.]

WISCONSIN

Scherocman and Schütz also provide the job mix formula gradation for the Wisconsin I-94 project in 1991. [It is similar to those provided by Bukowski (Reference 20) and Warren (Reference 25).] The authors note that the filler for this project was extremely fine. According to the authors, 39% of the filler was less than 20µm in size.

50. Scherocman, J.A.
The Design and Construction of Stone Mastic Asphalt Pavements, 1992.

This paper provides introductory information on the development of SMA pavements in Europe from the 1960s and in the U.S. from 1991. The author gives brief reviews of five SMA projects in the U.S. during 1991. [These reviews are similar to those given by the author in Reference 46 except that the Ontario SMA project description is replaced by the Indiana SMA project. The U.S. projects are reported in varying degrees of detail by other authors in References 20, 25, 31, 34, 35, 39, 40.] On the Indiana SMA project, the author observes that no fibers or polymers were used, but that a proprietary asphalt cement (designated MG 10-30) was incorporated to provide stiffness to the SMA. He notes also that the SMA in the Indiana project was produced through a drum mixer, and placed on the pavement using a windrow elevator and conventional paver. Both static and vibratory rollers were used to compact the SMA.

[The remainder of this paper addresses potential problem areas as seen by the author. No specific projects or studies are cited in this last part of the paper.]

The following points of interest arise from a reading of the paper:

1. The optimum asphalt cement content is sensitive to the aggregate gradation.
2. The gradation of SMA has evolved into the "30-20-10" rule:
    30% passing the 4.75 mm (#4) sieve,
    20% passing the 2.36 mm (#8) sieve,
    10% passing the 75µm sieve.
3. Mineral fillers used in Europe are very coarse compared with the ones used in the USA. In Europe, typically very little of the filler is less than 20µm material whereas in the USA, up to 80% of the filler could be less than 20µm size. Scherocman points out that the potential for extension of the binder (either asphalt cement alone or polymer modified binder) may give an optimum binder content under 50-blow Marshall design conditions in the laboratory that might not be related to field compaction conditions. Scherocman goes on to warn that it may not be correct to enforce a minimum asphalt content in an SMA mix simply because the design content is found to be less than the content commonly specified in Europe. The author points out that in Europe it is frequently not possible to design an SMA mix to meet

the minimum specified binder content; this is particularly the case when a polymer is used instead of one of the fiber materials.

4. Notwithstanding the laboratory design for determination of the optimum asphalt cement content, Scherocman recommends a visual assessment of the designed SMA after producing and compacting a trial mix of a minimum 200 metric tons.
5. The author does not mention the grades of asphalt cement used in Europe; but he does report on the grades used in five projects in the USA in 1991. These are:

Wisconsin I-94	85-100 penetration
Georgia I-85	AC 30
Michigan SR-52	AC 20
Missouri I-70	AC 20
Indiana I 70	MG 10-30

6. Scherocman notes that European practice requires double crushing of aggregates. In the USA this has been relaxed, particularly in areas where quarried rock is scarce. He says there is a need for determining how far the aggregate specifications can be relaxed before SMA performance is compromised.

51. Schröder, I., and Kluge, H-J.
Experiences with SMA, 1992.

[The text reviewed is an English version of the original: *Erfahrungen mit Splittmastixasphalt*.]

The authors begin by claiming that SMA was developed in the late 1960s by Zichner in the Central Laboratory of Strabag-Bau-AG to resist the damaging effects of studded tires. Although studded tires are no longer used in Germany, the demand for a hard-wearing surface remains. Schröder and Kluge note that the German SMA specification, included in ZTV-bit StB 84 (Additional Technical Regulations and Directives for the Construction of Bituminous Roadway Surfaces 1984) [Reference 10], was amended in 1990 as a result of experiences gained over the years. One of the changes was that the minimum binder content was raised from 6% to 6.5% by weight. They note also that the FGSV (Forschungsgesellschaft für Straßen und Verkehrswesen -- German Highway and Transportation Research Association) raised the minimum binder content (depending on the aggregates used) to 6.8% by weight.

According to the authors, failures of SMAs in the last few years can be attributed to mistakes in design, production, and/or placement. The need for homogeneity in the mixture is stressed. Possible reasons for fat spots in the SMA surface could be caused by drainage of the binder through inappropriately high mixing temperatures or stabilizing additives that do not perform as required. The authors believe that cellulose fibers almost invariably prevent binder drain off, even at relatively high temperatures. Also cited as a contributor to failure are high voids (insufficient mortar, assuming adequate compaction has been rendered), and aggregate quality.

Quoting from ZTV-bit StB 84, the authors say the following composition is required for SMAs 0/8 and 0/11 mm:

	Percent by Weight
Coarse aggregate	70-80
Sand and filler	20-30
Filler	8-13
Minimum binder	6.5
Stabilizing additive	0.3-1.5

Noting that the void content is low (2-4%), and that on many occasions the minimum binder content is 6.5 or 6.8%, the authors believe that from an economic standpoint it makes sense to strive for the minimum asphalt content. To accomplish this, the authors say that in doing SMA mix design it is appropriate to maintain the binder content while varying the gradation until the void range is met.

Schröder and Kluge offer information on stabilizing additives. Experience, they say, has shown that the mortar composition with softening points between 85°C and 100°C provides the required viscosity and impact strength. The authors cite two references in this connection: DIN 52011 and DIN 1996, part 15.

The authors say that according to a procedure ("Determination of Compactability of Rolled Asphalt by Means of the Marshall Procedure"), developed at the Technical University in Braunschweig, SMA is an asphalt mixture that cannot be easily compacted. They continue to say that it is more difficult to achieve 97% compaction with SMA mixes than with regular dense-graded base and surface courses. Schröder and Kluge believe that void content at design has a major influence on compactability.

52. Scherocman, J.A.
THE DESIGN, CONSTRUCTION AND PERFORMANCE OF STONE MASTIC ASPHALT PAVEMENT LAYERS, 1993.

This paper gives a brief description of the development of interest in SMA in Europe and lately in North America. Included are very brief summaries of the first five SMA projects undertaken in the USA in 1991. The remainder of the paper is similar in content to comments given by the author in the second part of Reference 50.

53. Milster, R.
Herstellen und Einbauen von Splittmastixasphalt - ein Erfahrungsbericht, 1993.
[Production and Construction of SMA - Report on Experiences.]

[This paper is not primarily about SMA mix design; however, it is useful to mix designers because the author explains some practical aspects in putting mix designs into practice.]

From his experiences, Milster notes that changes in aggregate sources can result in many different changes in SMA properties and appearance. He cites as examples, changes in color, particle shape, polishing resistance, and in-service performance. A change in aggregate source can also change bulk density, which can affect the air voids content. Metering of specific fillers is also important. Milster recommends using only manufactured sand from the crushing of high quality stone for SMA.

Milster provides a comparison of the ingredients for a typical dense-graded 0/11 [11 mm top size aggregate] HMA and an SMA 0/11S [for heavy traffic]:

	HMA 0/11	SMA 0/11S
Crushed stone 8/11 mm	20%	45%
Crushed stone 5/8 mm	15%	20%
Crushed stone 2/5 mm	15%	10%
Manufactured sand 0/2 mm	25%	13%
Natural sand 0/2 mm	15%	-
Filler smaller than 90µm	10%	12%
Mineral total by weight	100%	100%
Bitumen by weight	6%	6.7%
Additive stabilizer by weight	-	0.3%
Voids	3%	3%

In an interesting photograph, Milster shows a side-by-side comparison of the passing 2-mm mortar fractions of the above two mixes. The stable aspect of the SMA mortar, despite having almost twice as much bitumen as the dense-graded mortar, is most pronounced.

The mortar fraction compositions by weight are:

	HMA 0/11	SMA 0/11S
Natural sand 0/2 mm	27%	-
Manufactured sand 0/2 mm	45%	41%
Filler < 90µm	17%	38%
Bitumen	11%	21%

Milster warns that cellulose fibers should be stored dry and that extra dry and wet mixing cycle times can be expected in producing SMAs. In some instances, production may drop 25% compared with customary dense-graded mixes. He also advises not to store SMA in silos for more than three hours.

Good quality control is necessary and timely testing of the SMA as it is manufactured is needed. Milster illustrates this with a table of figures and a graph of sample height against number of blows of Marshall compaction. The graph shows a calculated curve and measured values. According to Milster, as long as the sample height is not more than three points different from the calculated height there is no need to test for other properties. A difference of more than three points is taken as a danger signal. [Milster provides a formula, which he does not explain. It appears to be associated with the calculated curve values.]

The remainder of Milster's paper deals with placing and compaction of SMA. Of note are the following points:

1. Compact immediately after placing.
2. Compaction should begin at 140°C and end before 80°C to avoid aggregate fracturing.
3. Available rolling time is important. Milster provides a useful chart showing cooling curves for a 35-mm thick pavement layer in summer sunshine and cold, windy conditions in the fall. In the summer, there appears to be about 30 minutes available for compaction before the mat temperature drops to 80°C whereas in the fall there might be only 10 minutes available before the critical 80°C is reached.
4. With SMAs, there is little reorientation of particles during compaction.
5. If a vibratory roller is used, no more than three passes should be made to avoid crushing of the aggregate. Do not use vibratory compaction on thin layers of SMA on rigid bases.
6. Three-wheeled rollers are preferred.
7. For skid resistance, use mechanical spreading to apply lightly coated 1/3 mm sand or 0/2 mm manufactured sand at 2 kg/m^2 while the SMA is still warm.

54. Karnemaat, R.J., Vreibel, D.J., and Van Deusen, C.H.
Stone Matrix Asphalt: Introduction of Loose Cellulose Fibers into Drum Mix Plants, 1993.

The main thrust of this paper relates to the handling of cellulose fibers and the metering of the fibers into the mix at the asphalt mixing facility. However, the authors provide some information that will be of interest to mix designers.

Cellulose fibers, the authors say, are available in compressed form in polythene bags and in pelletized form, in which fibers and asphalt are combined in equal percentages by weight. According to the authors, the pelletized version has been used in drum mix operations and the loose fibers have been historically used only in batch mix asphalt plants. Karnemaat et al discuss the problems of failing to entrap loose fibers inside the drum mixer and the consequent accumulation of fibers in the baghouse, which can affect the mix if baghouse fines are reintroduced. There are also potential combustion hazards if fibers become airborne.

Uniform dispersion of fibers is essential for proper stabilization of the mastic in SMA. The authors describe equipment and drum plant modifications that they say will accomplish this.

55. Morris, G.R.
SMA, Arizona Link No Exaggeration, 1993.

This article appeared in the trade press, responding to an argument that began during a discussion of a paper by Scherocman [Reference 46]. The argument revolves around a claim that SMAs are little more than variations of asphalt rubber mixes developed in Arizona in the 1960s [Reference 38]. Morris contends that the asphalt rubber mixes, developed in Phoenix, and using crumb rubber from old tires, are SMAs. The viscosity of the asphalt rubber binder is high enough that increased binder content can be accommodated in the mix without segregation or drainage of the binder and without the need for high percentages of passing 75µm material. [The previous contention in 1992 (Reference 38), indicated that this had come about through "... recent technological advances..."]

Morris appears to close the door on the argument by temporizing that it is not important who originated SMA.

[Svec and Veizer (Reference 79) report on a laboratory study of SMA using cellulose fibers and crumb rubber with the German gradation band.]

56. *Multigrade Asphalt, Multi-Contender for Large Aggregate, Surface Course and SMA Mixes*, 1993.

This article in the trade press introduces the reader to some aspects of Multi-grade (MG) asphalt binders, relying on information attributed to Bill Wilkins. According to the article, the asphalt coats large aggregate with a thick, viscous film that does not drain easily from the aggregate, even at 350°F. At 275°F, the viscosity remains too high to measure, says Wilkins. [A graph showing a comparison in temperature susceptibility (viscosity versus temperature) of various Multi-grade asphalts and AC-5, AC-10, and AC-20 grades is extended to 280 °F.]

It is claimed that with a Multi-grade binder, the contractor can dispense with the need for fibers as a stabilizing additive. Superior properties on Thin Film Oven Testing, Tilt Oven Testing, and long term aging are also claimed for the range of binders.

57. Kriech, A.
Stone Matrix Pavements Require Special Technique, 1993.

The initial portion of this technical article in the trade press describes Multigrade asphalt cements and their role in preventing drainage of the mortar fraction in SMAs. Kriech goes on to discuss four projects in which a Multi-grade asphalt cement (designated MG 10-30) was used. [All projects are presumed to be in Indiana.]

PROJECT #1--County Road 350, Bartholomew County

Three Sma trial sections were placed, using AC-20 and polyester fibers, AC-20 and cellulose fibers, and MG 10-30 with no stabilizing additive. [Both types of fibers were added at 0.3%.]

No mineral filler was added and the target densities in the field were not met for any of the designs although the MG-10 mix was fairly close.

PROJECT #2--Central Avenue, Columbus

AC-20 with cellulose fibers, and MG 10-30 were used in two SMA sections. Mineral filler was used. The author says that low densities in Project #1 led to a mixture redesign, involving the addition of filler and the reduction of asphalt in the mixture. According to an accompanying table, the AC-20 content was 6.8% and the MG 10-30 content was 7.0%.

PROJECT #3--Spear Avenue, Bartholomew County

Two SMA sections (one with AC-20 and cellulose fibers, and the other with MG 10-30), and an open-graded friction course with MG 10-30 binder were placed. For the SMAs, the design was:

Coarse Aggregate	75%
Fine Aggregate	20%
Mineral Filler	5%
AC-20	6.8%
MG 10-30	6.5%

[Gradation are not provided by the author but the percent passing the 75μm sieve would seem to be low in comparison with most other SMA projects.]

PROJECT #4--I-70 near Richmond

Kriech provides gradation, asphalt cement content, and voids results from eight cores as well as the job mix formula (JMF). The averages of the eight core results and the JMF are shown below. [The author does not say which grade or grades of binder and what fibers (if any) were used.]

Sieve Size	Percent Passing	
	Average of 8 cores	JMF
½ in.	96.8	94.6
#4	32.1	25.2
#30	17.9	15.1
#200	10.9	9.8

The average asphalt cement content for the cores was 6.0% compared with the JMF of 6.3% and the average air void content was 6.0% compared with the JMF of 2.5%.

Kriech notes the both batch and drum mixers gave consistent results. He also says that high aggregate quality with resistance to abrasion and polishing is needed to ensure long term performance. [However, no aggregate quality test results are provided in the article.]

58. Kuennen, T.
Pre-Mix SMA Fibers with Asphalt Cement, 1993.

This trade press article is edited by Kuennan from a paper by Karnemaat et al [Reference 54]. As in the original paper, Kuennan discusses the role of fibers in SMA, the problems of incorporating fibers in drim mix operations and recent solution to those problems. Arrangements at two parallel flow drum mixers in Michigan, and at one parallel flow mixer in Maryland are described briefly.

59. Reinke, G.
Laboratory Investigation into the Impact of Polymer Type, Polymer Concentration, and Aggregate Gradation on the Properties of Stone Matrix Asphalt Mixes, 1993.

In the preamble to reporting a laboratory study, Reinke notes that the typical European SMA design calls for the use of organic or inorganic fibers to stabilize the asphalt cement used in the matrix of the mix. In some instances, polymer-modified asphalts are used, sometimes with and sometimes without fibers.

Believing that polymer-modified binders are not only easier for the SMA producer to handle but also that fibers may increase the stiffness of the liquid binder at low temperatures to an undesirable extent, Reinke designed a laboratory study to investigate how SMAs are affected by two types of polymers (SBS--Styrene Butadiene Styrene, and EMA--Ethylene Methacrylate), and aggregate gradation.

The experiment was statistically designed, according to the author, using the following materials:

ASPHALT CEMENT

85-100 penetration grade at 5.5%, 6.0%, and 6.5%.

POLYMERS

SBS and EMA at 4.0%, 5.5%, and 7.0%.

AGGREGATE

1. Crushed limestone (double crushed).
2. LA Abrasion 30-35%.
3. Filler: fly ash. [Type not identified.]
4. Gradation:

Sieve Size mm	Percent Passing
12.5	95-98
9.5	75-90
4.75	27-42
2.36	18-33
75μm	5-12

Particle size analyses of the fly ash and the passing 75μm limestone material were performed and the results are provided in the range of 700μm to 0.9μm for both materials. [The method used is not stated.] The table shows that of the limestone material that was less than 75μm, 30.1% was smaller than 22μm. In costrast, 60.2% of the fly ash was smaller then 22μm. Up to 10% fly ash was used in some samples. According to Reinke, no statistically significant results could be attributed tot he fly ash.

TESTING

In preparing the mixes, the author says theat the goal was to have the binder between 300 and 400 centipoise viscosity at the time of mixing. This was achieved with the exception of 7% EMA.

The properties measures were:

1. Voids (bulk specific gravity and theoretical maximum specific gravity, using dryback analysis per ASTM D2041).
2. Resilient Modulus at 0, 13, 25, 38, 49, and 60°C (testing performed by Koch Materials Co., using a Retsina Mark IV).
3. Tensile Strength at 25°C.
4. Confined Dynamic Creep at 60°C (performed by NCAT).
5. Confined Static Creep at 60°C (performed by NCAT).

Using a best-fit model, the author develops a summary effects table from the generated results, highlighting the input variables that most significantly influence a given response.

Reinke's conclusions can be summarized as follows:

1. Material passing the 2.36 mm sieve acts like a filler for the large voids in the coarse SMA mix.
2. For most 12.5 mm SMAs, a range of 15 to 25% for the percent passing the 2.36 mm sieve would probably be best. [This satisfies the "20" part of the "30-20-10 rule".]
3. Three percent voids should be easily obtained by maintaining the passing 2.36 mm sieve material within the range 15 to 25%.
4. Keeping the passing 4.75 mm sieve material low is desirable for voids but greater amounts help to increase the stiffness modulus at elevated temperatures. Accordingly, 30% passing the 4.75 mm sieve seems like a good compromise. [This satisfies the "30" part of the "30-20-10 rule".]
5. The level of passing 75µm sieve material does not appear to be significant to mix performance. Reinke believes that the passing 75µm sieve material would probably be adequate within the range 6 to 9%. [This would not meet the "10" part of the "30-20-10 rule".]
6. A polymer content of 5 to 6% appears to be adequate.

60. Campbell, B.E.
Evaluation of a Stone Matrix Asphalt Overlay over PCC, 1993.

Quoting the experience that overlays on portland cement concrete (pcc) pavements are more susceptible to rutting than overlays on flexible pavements, Georgia Department of Transportation felt a need to evaluate the use of SMAs on pcc pavements. Test sections were placed on I-75 in October 1992. The author reports on mix designs, SMA production and placement, and provides some material test results.

MATERIALS

1.	Aggregatesource:	Tyrone.[Geological type not identified.]
	Aggregate properties:	
	LA Abrasion	41%
	Flat & Elongated Particles	29% (3:1 ratio)
		3% (5:1 ratio)
2.	Asphalt cement grade:	AC-20 Special.
	(AC-20 Special is defined as AC-20 with a penetration not more than 80, and initial viscosity at 77°F of not less than 2.3 million poises (AASHTO T-202), or not less than 2.5 million poises (ASTM D-3205)).	
3.	Asphalt modifier:	SBS polymer.
	Dosage	3% by weight of asphalt cement.
4.	Mineral filler:	
	Type	Marble dust.
	Particle size range	30-300µm.
5.	Stabilizing additive:	
	Type	Cellulose fiber
	Dosage	0.3%approx. by weight of total mix, but replacing a portion of aggregate weight.
6.	Hydrated lime dosage	1% by weight of aggregate.

MIX DESIGN

1. 50-blow Marshall compaction.
2. Laboratory mixing temperature was 325°F.
3. Laboratory compaction at 310-325°F.

A summary of information used to determine the optimum asphalt cement contents for the coarse and fine SMAs is provided. [The unit for fiber thickness is not given by the author. It is understood to be micrometers (µm). The method used to measure fiber thickness is not described.]

Fibers were also used in the standard dense-graded HMA (designated mix type E). [The fibers in this mix were thinner than the ones in the SMAs. No explanation is offered for this difference.]

The following is extracted from the summary:

SMA Type	Asphalt Cement Content %	Voids %	VMA %	VFA %	Fiber Thickness µm
Coarse	5.5	3.4	16.1	78.9	9.2
Fine	5.8	3.8	17.1	77.8	9.9
E	5.1	4.9	16.5	70.3	7.4

A few points are worth noting about the production and placement of the mixes:

1. A storage silo was used but no more than 50 tons of SMA were stored at any given time to prevent drainage of the binder. [The report does not mention if any binder drainage test was used in the mix design process.]
2. Fibers were introduced in trial mixes at both the lime and asphalt cement injection points but there was no conclusion as to which was the better method.
3. Modified asphalt cement was delivered to the mixing facility and pumped directly from the tanker truck. Some problems arose when the modified binder cooled before production started, resulting in pumping difficulties.
4. Plant mixing temperature was 340°F; field placement temperature was 325°F.
5. The author notes that quality control was quite good, the exception being the material passing ½ in. sieve, which was high for the coarse SMA. The JMFs were:

Sieve Size	Percent Passing	
	SMA Coarse	SMA Fine
¾ in.	100	100
½ in.	62	100
⅜ in.	44	80
#4	-	37
#8	20	25
#50	11	12
#200	8	8
% AC	5.5	5.8

6. Results from Georgia DOT's Loaded Wheel Rut Testing Device were (inches/8000 cycles):

Mix Type	Plant Mix	Roadway Cores
Conventional E mix	0.103	0.095
Fine SMA	0.122	0.126
Fine SMA (without fibers)	0.085	0.131
Coarse SMA	0.136	0.120*

*Fine SMA over Coarse SMA composite sample.

Georgia DOT's supplemental Specifications [Reference 32] are attached to the report.

[Attached to the review copy were two handwritten JMF sheets, one of which relates to a Type E mix asphalt rubber. This mix was apparently used in trials on the I-75. However, no reference to this mix is made in the report.]

61. Haddock, J.E., Liljedahl, B., and Kriech, A.J.
Stone Matrix Asphalt in Indiana, 1993.

The coarse aggregate skeleton principle of SMA, the binder-rich mortar design, and the proportioning of the coarse aggregate and mortar are explained in a philosophical introduction by the authors. Size and number of smaller particles are important considerations, say the authors, to ensure retention of the primary skeleton in service. Based on estimated cavity size, the authors believe that primary aggregate particles weigh about 15 times more than secondary particles. Hence, the total weight of secondary particles should be about 1/15 of the total weight of primary particles. The weight relationship, they say, will hold true if the large particles are approximately 2.5 times larger than the secondary particles. As an example, the authors say that a 16-mm particle will weigh about 15 times more than a 6-mm particle. [This principle should provide designers a starting point for blending aggregates.]

A binder-rich mortar holds the stone skeleton together and provides durability. The authors say that experience indicates 23 to 26% asphalt cement by total mortar weight is a desirable level. The aggregate part of the mortar is generally taken to be the material smaller than 2 mm, i.e., passing the #10 sieve. The authors believe that an appropriate mortar composition can be achieved by blending this minus 2-mm material with mineral filler so that 40 to 50% passes the 75µm sieve.

Using the aforementioned principles, an SMA was designed and placed on I-70 in Indiana in October 1991. The remainder of the paper describes the project. The following is a summary of the more important points.

AGGREGATE

1.	Coarse aggregate	16 mm dolomite containing at least 10.3% elemental magnesium.
2.	Fine aggregate	minus 4.75 mm sieve dolomite.
3.	Filler	ground limestone $\geq$ 85% passing 75µm sieve.

ASPHALT CEMENT

A table shows specifications for Indiana DOT AC-20 and a Multi-grade modified asphalt cement, designated MG 20-40. [The grade of asphalt cement is not identified in the text.]

MIX DESIGN

The following steps were used:

1. Voids in the coarse aggregate skeleton were calculated after compacting the 16 mm stones with a vibrating hammer in an 8-inch diameter mold.
2. For the mortar aggregate, 100% passing the 2-mm sieve was selected to give 44% passing the 75µm sieve.
3. Asphalt cement content was selected at 25% by weight of the mortar, i.e., mortar aggregate plus asphalt cement.
4. A theoretical calculation was made to determine the amount of mortar required to fill all but 3% of the voids in the coarse aggregate skeleton. [The authors do not provide details of the calculation.]
5. A trial mix was prepared using a 50-blow Marshall compaction effort. This produced an SMA with 5% air voids.
6. Keeping the asphalt cement content constant, the mix was fine-tuned by making minor changes in the coarse aggregate and the amount of mortar. [The design asphalt cement content was 6.5% by weight of mix and the air voids were 2.5%.] The final blend was 75% coarse aggregate, 20% fine aggregate, and 5% mineral filler. The JMF gradation is shown below.

Sieve Size	Percent Passing
¾ in.	100.0
½ in.	94.6
⅛ in.	30.9
#4	25.2
#8	24.0
#10	22.4
#16	19.0
#30	15.1
#50	12.8
#100	11.4
#200	9.8

The next section of the paper relates to field construction, results, and the authors' conclusions. The following points are worthy of note.

1. A drum mixer was used to produce the SMA.
2. A calibrated vane feeder on the filler silo delivered the requisite amount of filler, which was introduced in the drum at the same point as the asphalt cement.
3. Maximum mix temperature leaving the plant was 325°F.
4. The breakdown roller was a 9-ton, 3-wheel, static, kept close to the paver; the finish roller was a static, ballasted, tandem roller, giving a total weight of 14 tons. Two passes with each roller were applied.
5. Although the design asphalt cement content was 6.5%, the effective asphalt cement content was 6.3%. The difference, say the authors, may be due to absorption. The Indiana DOT method for determining absorption requires that the mix be held at compaction temperature for one hour before extracting the recoverable asphalt cement. This amount then becomes the effective asphalt cement content. The authors recommend extending the holding period to four hours.
6. The average gradation of core samples was finer than the gradations of truck samples and the JMF. Haddock et al attribute this to the coring procedure, which, in a high-stone content mix affects the gradation.
7. The authors stress that in designing SMAs, the aggregate skeleton should be developed and the mortar content varied until the correct air voids range is reached. This, say the authors, is a significant difference from regular HMA mix design.
8. Constant paver speed is important because mortar segregation can occur if the paver augers rotate at too high a speed. [No segregation is reported in the text. A windrow pick-up machine delivered the SMA to the paver. So, it is assumed that this advice is from past experience.]
9. Too much water on the rollers can cause the mortar to foam and produce fat spots.
10. Rollers should not be operated in the vibratory mode, which can cause flushing of the mortar.

62. Bukowski, J.R.
SMA in America, 1993.

Bukowski reviews the general principles behind SMA, with particular reference to the development of the mix in Europe and its recent introduction into the U.S. The author refers to a series of field trials in five states in 1991 and says that all are performing well. A summary chart for the five projects in 1991 is included in the report. [See Reference 20.] A chart is also included for the 1992 SMA projects.

From the experiences gained through these projects, the author makes preliminary findings, among which are the following:

1. A critical sieve is the #4. Material passing it should be 30% or less.
2. The amount of mineral filler less than 75µm should be limited to not more than 3% of the total aggregate.
3. Not more than 20% of the coarse aggregate should have a length to width ratio of 3 to 1.
4. Fibers can be used in both batch and drum mix facilities.
5. Mixing times in batch plants (5 to 15 seconds dry mix cycle) are less than originally expected.
6. Paving speeds of between 30 and 40 feet per minute can be used without any detriment.
7. Breakdown rollers should be operated close to the paver and all compaction should be completed before the SMA cools below 260°F.
8. Vibratory compaction should be limited because of flushing of the mastic and fracturing of the aggregate.

Turning to the future, Bukowski makes a number of points, many of which draw attention to what needs to be developed. [The value of these points from Bukowski is that they represent not only a state of knowledge on what seems to work but also the gray areas of SMA as they were at the beginning of 1993. The author's concerns on production aptitude are also expressed.] Among the points made are the following:

1. Gradations should continue to follow the "30-20-10 rule" of 30% passing the #4, 20% passing the #8, and 10% passing the #200 sieves.
2. Durable crushed aggregate should be used.
3. The type and quantity of passing #200 sieve material need to be fully examined.
4. Most SMA projects in the U.S. have used AC-10 or AC-20 grades of asphalt cement or equivalent. Other grades for various climates need to be examined.
5. Generic fiber properties are being developed and may lead to the use of more economical domestic supplies.
6. The best approach for binder stabilization (fibers or polymers) is unresolved.
7. Laboratory compaction using 50-blow Marshall effort is the normal practice. Gyratory compaction, which produces lower air voids, is being investigated.

Traditional markers of flow and stability have less relevance with respect to SMAs than with conventional HMAs.

8. Many HMA facilities in the U.S. lack the ability to feed accurately the required quantities of mineral filler.

63. McDaniel, P.
Evaluation of Stone Mastic Asphalt in Missouri
Route I-70, Boone County, 1993.

Following the initial experience with SMA in Missouri in 1991 (Reference 34), two additional SMA test sections were placed on I-70 in 1992, one with cellulose fibers at 0.3% and the other with mineral fibers at 0.5% by weight of mix. A batch mix plant was used to produce the SMAs and no problems were encountered with mix production. However, tearing, bleeding, and tender mix problems were experienced during placement. The tearing problem was solved by judicious folding of the wings of the paver hopper; but the reasons for the other two problems defied identification.

MIX DESIGN

1. The design parameters were the same as those used previously except that the gradation is slightly different, being slightly coarser on the ⅜-in. sieve and a little finer on the passing #200 sieve:

Sieve Size	Percent Passing by Weight
¾ in.	100.0
½ in.	97.9
⅜ in.	70.4
#4	33.9
#8	18.5
#16	14.6
#30	13.7
#50	13.3
#100	12.7
#200	10.1

2.	Marshall compaction	50 blows.
3.	Air voids, percent	3-4
4.	Flow (1/100 in)	8-15
5.	VMA, percent	16 min.

6. VFA, percent 78 min.

MATERIALS

The mineral filler was from the same source as before. [The gradation passing the #200 sieve is not given but as it is from the same source, it presumably had 48.5% or so smaller than 20µm (Reference 34) and did not meet the author's previous recommendation of 0 to 5% smaller than 20µm.]

The aggregates appear to be the same as before or are at least similar. Because of shortages of the kind of quality aggregates that are used in SMAs in Europe, compromises were made in Missouri by using 50/50 blends of limestone and porphyry. Both easily passed the sodium sulfate soundness test but the limestone was a little high on Los Angeles Abrasion (38-40).

In an appendix, a special provisions clause states that the aggregates shall be approximately 40% crushed limestone, 50% crushed porphyry, and 10% mineral filler. Flat and elongated particles are not to exceed 20%, based on the 3:1 ratio.

The asphalt cement grade was AC-20 and the content was 6.6% or 6.7%. Original and recovered asphalt cement properties are given in an appendix.

The remainder of the report deals with construction details. Of note are the following findings:

1. Stone-on-stone contact was established on the initial roller pass.
2. Mat density remained unchanged at mat temperatures between 220 and 280°F but increased with roller passes below 220°F.
3. Breakdown rollers were used in the static mode except for one small area where the vibratory mode was used after one pass in the static mode. Vibratory-mode rolling did not decrease the number of passes to achieve 98% density but did produce some crushing of the coarse aggregate and was therefore discontinued.
4. Sanding of the surface for skid resistance purposes was not required.

64. Tahmoressi, M.
New Coarse Matrix High Binder Mixes, 1993.

In this brief article, the author claims that the Texas Department of Transportation has developed a new type of design procedure for high stone-on-stone content mixes.

Furthermore, according to the author, the mixes do not require additives or fibers and are not expected to segregate or rut.

The initial step in the design procedure appears to be the preparation of mixes with several percentages of coarse aggregate concentration. Gyratory compaction is used for each mixture, the asphalt cement content being held constant. After fabrication, the relative density of each set of specimens is measured and plotted against the coarse aggregate content (Percent retained on the #10 sieve). This curve yields an optimum stone-on-stone coarse aggregate matrix at the maximum relative density and a corresponding value for the amount of coarse aggregate. However this optimum value is not selected as the design point because of expected degradation during production. Instead, the author recommends increasing the coarse aggregate to a range between 2.5 and 5% higher than the coarse aggregate optimum.

The author refers to Texas Method Tex-232-F and states that a static creep test (Test Method Tex-231-F) is also part of the procedure. [No details are provided in the article.]

65. Francken L., and Vanelstraete, A.
New Developments in Analytical Asphalt Mix Design, 1993.

In Belgium, an analytical method of mix design for dense-graded bituminous mixes was proposed by the Belgian Road Research in 1987. The authors say that the following steps were used:

1. Evaluating the proposed volumetric composition of the mix based on the mineral aggregate characteristics.
2. Calculating the maximum volume of mastic without overfilling the mix.
3. Determining the composition of the mastic.
4. Experimental verification.

Francken and Vanelstraete propose an extension of the earlier work to cater for open-graded and SMA mixes, which could not be designed properly by the previous method. The theoretical background to the procedure is presented. However, the authors warn that the computations needed for the evaluation procedure are very long and difficult to do without a computer program. A special software called PRADO has been developed to facilitate learning and application of the procedure. A series of five programs (BINDER, SAND, GRADING, MIX DESIGN, and PROPERTIES) is intended to provide digital and graphical information to the mix designer. The voids evaluation procedure is incorporated as subroutines in SAND (voids in sand mixes), GRADING (voids in aggregates), and MIX DESIGN (voids in the skeleton). According to the authors, the original procedure, which was developed for 100% Marshall compaction, can be adjusted to other compaction levels. [It is not clear what the authors mean by 100% Marshall compaction.]

Francken and Venelstraete report that a large number of verifications were done on sand or stone skeleton mix types. The results, they conclude, show the ability of the procedure to predict VMA values in the range of 14 to 36% and voids in the sand plus stone skeleton in the range of 20 to 50% within an accuracy of 1%. The procedure, say the authors, takes into account the following factors:

1. Particle size distribution (the grading curve).
2. Relative size of particles.
3. Particle angularity.
4. Packing mode (filling or substitution). [This term is not explained.]
5. Relative compaction (96, 98, and 100%). [It is not clear what the authors mean. Presumably it is connected with the 100% Marshall compaction mentioned above.]

At the time the paper was presented (June 1993) an English version of the software was in preparation.

66. Grosshans, D., Shivarov, I.I., and Nikolova, S.K.
First Attempts in the Appliance of Splittmastix Asphalt in Bulgaria, 1993.

Inspired by the apparent success of Splittmastixasphalt in Germany, the authors relate in this very brief paper the laboratory work involved in leading to the first trial section of Splittmastixasphalt in Bulgaria. The design is based on the German standard ZTV bit-StB 84 [Reference 10].

Ingredients of the two mixes investigated were:

Material	Percent by mass	
	0/8 mm	0/12 mm
Chippings 8/12	-	42.0
Chippings 3/8	71.0	23.0
Sand	13.0	9.5
Dust	0.9	0.9
Hydrophobic Filler	8.2	8.2
Thixotropic Additive	0.3	0.3
Bitumen	6.6	6.6

[Presumably the filler was lime and the stabilizing additive was cellulose fibers.]

The gradations used were:

Sieve Size mm	Percent Passing 0/8 mm	0/12 mm
11.2	100.0	100.0
8.0	97.0	74.0
5.0	38.0	32.0
2.0	21.0	23.0
0.71	17.0	16.0
0.25	14.0	13.0
0.071	10.0	10.0

Wearing course tests applied in Bulgaria were conducted on the 0/8 SMA without additive, the 0/8 and 0/12 SMAs with additive, a dense-graded fine asphalt. These tests are:

Resilient Modulus at 10°C at 1, 4, and 10 Hertz.
Failure strain at 10°C at 1, 4, and 16 Hertz.
Fatigue ratio at 10°C and loading frequency 16 Hertz.

The highest resilient modulus was achieved with the 0/8 SMA without additive at 4 Hertz (2620 MPa), and the lowest resilient modulus came from the dense-graded fine asphalt at 1 Hertz (1510 MPa). The dense-graded fine asphalt also had the lowest failure strain at any frequency (generally by a factor of two), and the lowest fatigue ratio.

67. Harders, O.
Effect of Mortar Stabilizers in Split-Mastic-Asphalts, 1993.

In addressing mortar stabilizers, the author reviews the general principles of SMA and the need for some kind of structural viscosity in the mortar to prevent drain off. He notes historically the replacement of the original asbestos fibers with cellulose, rock, glass, or synthetic polymer fibers. Also cited are synthetic silica, diatomaceous earth, grinded aero-concrete, fly ash, natural asphalt, and homogeneous polymer-modified binders.

A comparison of several materials was made in a test study, in which the gradation and binder content were kept constant.

The mix composition was given as follows:

Aggregate 5/8	53.2%
Aggregate 2/5	18.7%
Crushed sand	12.1%
Limestone filler	9.4%
Binder content	6.6%

[Aggregate type and tests are not mentioned.]

The selected gradation is given as:

$<$ 8.0 mm	99.0%
$<$ 5.0 mm	45.0%
$<$ 2.0 mm	25.0%
$<$ 90µm	12.0%

Of the products tested, only the two types of polymer-modified binders are identified. The other materials are listed generically as:

1. Fibers — 3 types of cellulose
1 type of mineral wool.
2. Synthetically dispersed silica.
3. Diatomaceous earth.
4. Natural asphalt.

The bitumen grade was B 65.

Mortar viscosity was compared by using the softening point test (ring and ball -- R & B) on the mix of binder, limestone filler, and stabilizing additive. The lowest R & B result (64°C) came from the control mix and the natural asphalt mix. This was closely followed by the diatomaceous earth mix. All others were between 75 and 83°C, with the three types of cellulose occupying the top places, closely followed by one of the SB polymers.

Marshall testing was done and compared with rut testing according to the City of Hamburg modified wheel tracking device. The author concludes that there is insufficient correlation between Marshall stability and rut testing results. In the summary of the paper, Harders says that a rolling pin was used to compact slabs for rut testing. The slabs were compacted to 98 to 101% of a reference specimen. The rut testing is done under water, using about 20,000 wheel passes at 50°C under a pulsing load of 720 N. Sinusoidal loading is applied through flat, steel wheels (diameter 204 mm, width 47 mm) at about 1 km/hr. Harders concludes from the rut testing results that homogeneous polymer-modified binders, such as the ones used, produce the best effect.

68. Scherocman, J.A.
The Design, Construction, and Performance of Stone Mastic Pavement Layers: the Continuing Story, 1993.

[This paper is essentially an extension of a previous paper (Reference 52), except that the author discusses what he perceives as problem areas in SMA, from laboratory mix design through to compaction in the field.]

Scherocman notes that the total binder contents of SMAs will vary according to the type and amount of mineral filler being used. To help the reader's understanding of the expected changes in total binder content that could be expected with each type of stabilizing additive, he hypothesizes the use of an unchanging SMA gradation as follows:

1. SMA mix with polymer additive -- total binder content 6.0%.
2. Same gradation of SMA with mineral or inorganic fibers -- total binder content 6.2% to 6.4%.
3. Cellulose or organic fibers -- total binder content 6.5% to 6.7%.

Having set the scene, as it were, for the scale of changes in total binder content that one could normally expect, Scherocman criticizes many SMA mix designs in the USA for violating the above trend. He reports an instance in which the total binder content of a polymer modified SMA was 0.8% higher than that of the same aggregate type and gradation that incorporated a cellulose type of carrier. He discusses another instance in which a design using fiber and AC-5 asphalt cement was 0.8% less than the optimum total binder content for the same fiber mix with AC-20 grade asphalt cement. Also discussed are inconsistencies in laboratory mix design test results involving a polyolefin additive.

On aggregate gradations, Scherocman cautions against the application of variations on the so-called "30-20-10 rule" because of limited experience with such variations in North America and even in Europe.

Also criticized by the author is the application of a Marshall stability criterion by some states. Instead, the author suggests dynamic creep or indirect tensile creep may be more meaningful. The author says that several states [unnamed in the paper] have specified a minimum Marshall stability of 1,500 pounds for SMA mix designs but that for many SMA mixes 1,500 pounds is difficult to obtain, and that in many cases contractors have had to obtain other aggregates, alter gradations, or change the type and gradation of the mineral filler. While noting that the Federal Highway Administration Technical Working Group on SMA recommended in a July 1993 draft specification a minimum Marshall stability of 1,400 pounds, Scherocman feels that experience in North America indicates that 1,200 pounds is a reasonable minimum value.

Other suggested criteria from the author are:

1. Marshall flow 8 to 16.
2. VMA minimum 17%.
3. Optimum binder content should be selected at 3.5% air voids. [No study is cited but the author discusses experiences with 3% design voids and total binder contents of 6% or even 6.7% resulting in low voids in the field -- 1.9% after construction reduced to about 1.7% a year later, although no flushing occurred.]
4. Following on the preceding point, the author believes that specifying a minimum binder content is not only unnecessary but also incorrect.

Discussed briefly are problems arising in the production and construction phases of SMA. These problems may have some bearing in explaining why some laboratory designed SMAs do not behave as expected in the production and construction phases. Before closing down the asphalt mixing facility and calling for a redesign of the SMA, the points in the following summary should be considered:

1. In most projects, delivering the mineral filler directly into the weigh hopper in batch mixers or into the rear end of drum mixers has worked well.
2. In batch mixers, a modification of the scale to read in increments of one pound instead of 10 pounds has generally been necessary. In the drum mixers as well as the drum dryers of batch mixers, pick up of filler in the exhaust gas stream has occurred due to attempts to feed the filler through the fine and coarse aggregate cold feed bins. This can cause excess fines in the baghouse and may provoke shutting down the plant. In drum mix operations, Scherocman recommends feeding the filler pneumatically, either separately or in combination with fines that are returned from the baghouse, into a "mixing box" inside the drum. [The "mixing box" is a protected zone in drum mixers where the asphalt cement is injected in a spray to entrap returned fines from the baghouse.]
3. The author briefly reviews the development of methods to introduce fibers (organic or mineral). Specialized equipment is now used to add loose fibers directly into the pugmill in batch mixers or into the rear end of drum mixers.

4. According to the author, draindown has occurred when the "optimum" binder content of the SMA is too high for the void content (VMA and voids) of the mix; and furthermore, it is the total binder content of the mix and not the type of additive used that contributes to draindown.
5. The influence of mix temperature on draindown is also discussed. Several practical suggestions are given to solve the problem. These are:
   (1) Reduce production temperature by steps of at least 10°F up to a maximum reduction of 30° F.
   (2) If temperature reduction fails to effect a cure for draindown, reduce the binder content by steps of not more than 0.2% to a level of 0.4% below the job mix formula.
   (3) Redesign the SMA.
6. Scherocman notes that SMA mixes should be very stable under compaction and that rollers can overhang unconfined edges without displacing the mix. He also advises that because SMA layers are thin (typically 1½ inches or less), and stiffer than dense graded mixes, they need to be compacted quickly to achieve the required density. He warns that "cold rolling" by finish rollers have decompacted some SMAs and he recommends that the finish roller, if used at all, should be operated within 500 feet of the paver.

69. Brown, E.R., and Manglorkar, H.
Evaluation of Laboratory Properties of SMA Mixtures, 1993.

In this report, Brown and Manglorkar begin with a review of SMA development in Europe. They provide typical gradation charts and the essentials of SMA components and mix design. Lists of SMA projects (some placed in 1991 and 1992, and others planned for 1993) are included. The approach adopted for designing U.S. projects relied on European experience and the authors note that the transfer of European SMA technology to the U.S. needs the evaluation of the influences of several factors. Accordingly, the main thrust of this report centers on using existing laboratory methods to predict the performance of SMA mixes. The approach taken by the authors is to vary the types of aggregates (two typical aggregates were used) and fibers (three), and to vary the contents of the fine aggregates, filler, and asphalt cement in the mix. One of the aggregates, a granite, had a Los Angeles Abrasion value of 35% (considered marginal, say the authors, by then-current FHWA guidelines for SMA). The other aggregate was a siliceous gravel, which had a Los Angeles Abrasion value of 46.5% (unsuitable, say the authors, according to FHWA guidelines).

The asphalt cement was AC-20 grade. Stabilizing additives were domestic (U.S.) and European cellulose fibers, and European mineral fiber. The filler was obtained by screening a local agricultural lime. [No gradation for passing 75µm is given.]

Air voids target was 3.5%. Laboratory compaction was 75 revolutions of the Corps of Engineers Gyratory machine set at 1° gyration and 120 psi vertical pressure. This compaction effort, the authors say, gives the same density as 50-blow Marshall. Dense-graded mix samples were compacted at 300 revolutions, which is the typical compaction effort for such mixes. Dense-graded mixes were included, not to evaluate whether or not SMA is a better mix but to help ascertain which tests may be applicable to SMA mixtures. The Gyratory was used so that specific engineering properties could be measured. The tests were:

1. Gyratory Shear Index.
2. Gyratory Elasto Plastic Index.
3. Shear Stress to produce 1° angle.
4. Marshall stability and flow.
5. Indirect Tensile Strength at 77°F.
6. Resilient Modulus at 40, 77, and 104°F.
7. Static Confined Creep at 140°F.
8. Dynamic Confined Creep at 140°F.

[Brown used the above approach also in evaluating the SMA placed in Michigan in 1991 -- Reference 48.]

The gradations of the granite and gravel dense-graded mixtures are different. However, the gradations for each type are typical of such mixtures in use. The SMA gradations for both aggregates were the same. For comparison, the JMFs for the percent passing the various sieve sizes are shown in the following table:

Sieve Size	Granite Dense Mix	Gravel Dense Mix	Granite & Gravel SMA
½ in.	100.0	100.0	100.0
⅜ in.	85.0	96.0	80.0
#4	67.0	82.3	29.0
#8	50.0	55.4	25.0
#16	30.3	35.7	19.0
#30	21.3	27.6	17.3
#50	15.0	17.8	16.2
#100	11.1	9.3	14.8
#200	6.7	5.6	11.6

Changes made in the gradations for SMA for both granite and gravel aggregates were:

#4 sieve	JMF - 5%, JMF +5%, JMF + 10%,
#200 sieve	JMF - 2.8%, JMF - 1.4%, JMF +1.4%.

These changes allowed variations in the #4 sieve from 24 to 39% and in the #200 sieve from 7.4 to 11.6% to be explored. Asphalt cement content varied from 4.5 to 6.5%, and the fiber contents varied from zero to .5%. The authors provide a useful flowchart for the various material combinations for the reader's convenience.

The authors note that most of the mixtures evaluated would not meet SMA requirements because of the low asphalt cement contents. Among the conclusions reached were:

1. SMAs with mineral fibers typically have lower optimum asphalt cement contents than SMAs with cellulose fibers.
2. Increasing fiber content slightly increases VMA and allows slightly more asphalt cement in the mix.
3. VMA is significantly altered by varying the percent passing the #4 or #200 sieves.
4. Shear strength of SMA decreases only slightly with increasing asphalt cement content.

5. Marshall stability requirements should be lowered or deleted from specifications for SMAs.
6. Marshall flow is higher for SMAs than dense-graded mixes, indicating that SMAs are more flexible.
7. Indirect Tensile Strength of SMAs was always lower than dense-graded mixes. Future studies should evaluate tensile strain at failure.
8. Resilient modulus values of SMAs were always lower than dense-graded mixes. The variability in resilient modulus for SMAs was high.
9. Static Creep values for SMAs and dense-graded mixes were about the same.
10. Under Dynamic Creep testing, SMAs usually had slightly higher permanent strain values than dense-graded mixes.
11. All three fibers appeared to be satisfactory. Changes in aggregate gradation, fiber type, and fiber content did not greatly affect the mechanical properties of SMAs when the optimum asphalt cement content was used.

70. Walsh, I.D.
Stone Matrix Asphalt Wearing Course, 1993.

This item is Clause 995 AK of the Kent County Council (United Kingdom) Standard specification for SMA. [Various British Standards apply to materials and test methods referenced in the document. The standards referenced are BS 594, BS 598, BS 812, BS 3690, BS 4987, and BS DD 184. The last-mentioned is a draft for development document, specifying a "Method for the Determination of the Wheel Tracking Rate of Cores of Bituminous Wearing Courses."]

The following points of interest arise from a reading of the specification:

AGGREGATE

1. Coarse aggregate must be crushed rock. Crushed or uncrushed gravel is not permitted. The coarse aggregate must have:
   Polished Stone Value not less than 55.
   Ten percent Fines Value not less than 180 kN.
   Maximum Aggregate Abrasion Value 12.
   Maximum Flakiness Index (passing 10 mm, retained 6 mm) 30%.
   [One has to refer to BS 812 for the appropriate tests.]
2. Fine aggregate shall be at least 50% crushed rock or gravel.

FILLER

Filler can be hydrated lime, Portland cement, or crushed limestone as described in BS 594.

BITUMEN

The grade of bitumen is 100 penetration (BS 3690). The target bitumen content is a minimum of 6.8% by mass of total mixture (tolerance from target ± 0.3%).

STABILIZING ADDITIVE

Only dry organic fibers containing at least 70% cellulose are allowed. The target range by mass of total mixture is 0.3 to 1.5% (tolerance from target ± 0.1%).

MIX DESIGN

1. Target air voids range is 2 to 4% (ASTM D 3203, ASTM D 2041, initial bulk density BS 598).
2. Compaction of laboratory slabs for the Wheel Tracking Test is done with a vibrating hammer to achieve at least 97% of Marshall 50-blow density.
3. The Wheel Tracking Test is carried out at 45 ± 1 °C, conditioned at this temperature for at least four hours before testing. The tire of the wheel has an outside diameter between 200 and 205 mm, with a width of 50 ± 1 mm and is of a specified hardness of rubber. The standard applied load is 520 ± 5 N. The application rate is 42 passes per minute.
4. The SMA must comply with a Binder Drainage Test. [This test is specified in Appendix A of the Transport and Road Research Laboratory's RR 323. A copy is reproduced below.]
5. Only one gradation (a 10 mm nominal size) is specified. The gradation requirement is:

BS Sieve Size	Percent Passing	Tolerances %
14 mm	100	
10 mm	90 - 100	± 5
6.3 mm	30 - 50	± 10
2.36 mm	22 - 32	± 5
75µm	8 - 13	± 2.5

The remainder of the specification relates to production and construction considerations. The following points are worth noting:

1. Maximum mixing temperature is normally 175°C.
2. Maximum storage time is 3 hours.
3. Transport trucks are required to be insulated and the minimum SMA temperature on delivery is 145°C.
4. There is a provision for spreading and rolling 3 mm to 75µm dust-free, crushed rock fines at least 600 gms/m² after the first roller pass.
5. Compaction is effected by at least two passes of a tandem roller of minimum deadweight 6 metric tons. The roller should be capable of vibration. [However, the specification is silent on vibration restrictions.]

71. Marek, C.R., and Dukatz, E.L.
Aggregate Production Requirements for Stone Matrix Asphalt, 1993.

By way of introduction, Marek and Dukatz provide the reader with a background review of SMA in Europe and the transfer of the technology to the U.S. through a series of field trials in 1991 and 1992. The principle of SMA's gap-graded, stone-on-stone contact through high coarse aggregate content is explained. The use of high filler and asphalt cement contents is discussed briefly. Also noted by the authors is the potential for binder draindown to be a problem in storage or in transit at high mix temperatures (310 to 320°F) to the paving site. To minimize draindown effects, the authors cite the use of cellulose and other fibers as well as polymer-modification of binders. However, according to Marek and Dukatz, crushed stone fines can also be used to inhibit draindown.

In addressing SMAs, the authors inform the reader that they are limiting their discussions to aggregate-related factors that influence the properties and performance of SMAs. They say the primary factors have been identified as:

1. Amount of coarse aggregate.
2. Gradation of aggregate.
3. Top size of aggregate.
4. Type and quantity of material smaller than 75µm.
5. Flat and elongated particles.
6. Abrasion resistance of aggregate.
7. Other quality factors.

Marek and Dukatz discuss each of the above factors in some detail and provide some criteria that have been applied in the U.S. to control these factors. Taken in the same order as above, their comments can be summarized as follows:

1. AMOUNT OF COARSE AGGREGATE

Quoting from an unpublished source, the authors say that currently designed SMAs combining 85% coarse aggregate and 15% fine aggregate give a VMA range of about 30 to 35% for the aggregate blend. They say that a minimum amount of coarse aggregate (material retained on the #4 sieve) must be about 60% to ensure the right skeletal structure and VMA.

2. GRADATION OF AGGREGATE

The authors note that only three out of the 16 gradations that were used in the U.S. SMA field projects conformed with the FHWA model specification [July 1993 version of the SMA Technical Working Group]. Marek and Dukatz believe that sufficient coarse aggregate will be present if up to 45% of passing #4 sieve material is used in the mixture. They say that additional study is needed to develop the optimum grading for stone-on-stone contact. Also noted by the authors is the "30-20-10 rule" (30% passing the #4 sieve, 20% passing the #8 sieve, and 10% passing the #200 sieve) currently used in the U.S. for the fine aggregate fraction.

3. TOP SIZE OF AGGREGATE

Marek and Dukatz note that most SMAs in the U.S. have been limited to ¾ inch top size aggregate because constructed thicknesses have been 1½ inches.

4. TYPE AND QUANTITY OF MATERIAL SMALLER THAN 75µm

The authors believe that this material should be the crusher dust obtained from the production of other high quality crushed stone. They say the material can be fines from limestone, basalt, or granite production, should be non plastic and not contain a high mica content. [However, they do not define "high mica content".]

5. FLAT AND ELONGATED PARTICLES

Briefly reviewed by the authors are the FHWA Model Specification (maximum of 20% of particles retained on the #4 sieve having a length to thickness ratio greater than 3 to 1, and a maximum of 5% being greater than 5 to 1); the European criteria (double crushed, cubical shape); and the original German specification (axial ratio to be less than or equal to 1.2). [According to Stuart (Reference 35) German practice is to reject stockpiles with more than 20% by weight of aggregates larger than 5 mm having a length-to-thickness ratio more than 3 to 1.] The authors support the criterion of a maximum of 20% not more than 3 to 1 ratio.

6. ABRASION RESISTANCE OF AGGREGATES

Marek and Dukatz take issue with the low abrasion loss numbers (30%) in Europe and more recently specified in the FHWA's Model Specification. They say that the low value was initially needed in Europe to resist wear from studded tires and they make the point that studded tires are not permitted in the U.S. The authors conclude that the application of the current Los Angeles Abrasion loss of 30% maximum is too stringent, unnecessary, uneconomical, and will eliminate many high quality aggregates presently produced in the south east U.S. They recommend that the value be the same as that permitted by state highway agencies for other surface course applications. [This is always an option that is open to a specifying agency. It is, however, unclear what effect such a relaxation might have on SMA performance. Trial SMA projects in the U.S. of recent origin and performances are subject to evaluation. Stuart (Reference 35) suggested 40%; McDaniel (Reference 34) reported 35% was allowed in Missouri; Campbell (Reference 60) reports that aggregate of Los Angeles Abrasion loss of 41% was used in Georgia; Brown (Reference 40) says that up to 45% was allowed in Wisconsin; and the revised FHWA Model Material and Construction Guidelines (Reference 81) stays with 30% maximum.]

7. OTHER QUALITY FACTORS

While agreeing that coarse aggregate for SMA should be high quality 100% crushed aggregate of low absorption, the authors complain that the current FHWA recommendation of 2% maximum absorption eliminates high quality, air-cooled, blast furnace slags, and limestones from high quality coral formations. The authors believe such materials should be allowed in specific regions.

Having dealt with the aggregate-related factors, the authors next, describe what they call an "SMA-like" project in Texas, using a Multi-grade asphalt cement and aggregate types and sizes that are more easily produced and readily available. This project had 5% passing the 75µm sieve. Two other projects are cited with passing 75µm percentages of 8 and 9. The authors say that no draindown occurred and that no fibers were used. [However, they do not provide the binder contents for any of the three mixes. It appears that no binder drainage tests were conducted as none are cited in the paper.] The authors admit that none of the gradations used comply with the FHWA's recommendations for SMA.

The final portion of the paper is an explanation of the difficulties facing a stone supplier to meet specialty products such as the gap-graded aggregates for SMAs. The authors' conclusion is:

"User agencies should identify these products that are readily produced and available for use in SMA mixes. Standard products rather than specialty products should be specified and used whenever possible."

72. Avera, L.T.
Getting Industry out of a Rut with Stone Matrix Asphalt Mix, 1994.

This trade press article provides comments from presentations that were made during the Hot Mix Asphalt (HMA) Conference in Atlanta, late in 1993. A positive working relationship has to be developed by the contractor with the aggregate supplier. Another state agency engineer related that unacceptable splotches and matting had occurred. He attributed the problem to low friction numbers in the mix design, according to Avera. Conceding that SMA had been very successful in Europe, an FHWA representative cautiously intoned that as far as the U.S. was concerned, "Time will tell."

However, the most compelling points in the article come, not from mix designers, but from a contractor, who, while admitting that the HMA industry collectively does not know everything about SMA, optimistically says that "... there is no reason to be intimidated by SMA." The contractor's spokesperson is Ron Pope and he provides a dozen practical tips for making SMA a success. Briefly, his points are:

1. Control of aggregate stockpiles is important. Have substantial stockpiles of tested materials before starting.
2. Make sure plant burner can operate steadily at desired production rate.

3. In production, keep targeting the center of the gradation band as indicated by test results.
4. Match plant production rate with paving and compaction capability.
5. Constantly check additive feed.
6. Watch out for high power demands on pumps, motors, and slat conveyor.
7. Keep paver moving. SMA cools rapidly and becomes unworkable when the temperature drops.
8. Keep roller close to paver.
9. If paver stops for over 15 minutes, be prepared to cut a new [transverse] joint.
10. Watch for screed tendency to rise as paver speed increases.
11. Longitudinal joints require more attention.
12. SMA is a special mix. Make sure everyone associated with it understands that.

73. Flynn, L.
U.S. Embraces Concept of Stone Matrix Asphalt, 1994.

In this trade press article, Flynn draws on delegates' discussions at the first U.S. Hot Mix Conference in 1993 to support his premise. Comments range from simple explanations of the stone-on-stone skeleton nature of SMA to the guidelines offered by the FHWA's SMA Technical Working Group (Reference 81). Flynn also reports that the most common grade of asphalt cement used in SMAs in the U.S. is AC-20, which is said to resemble closely the grades used in Germany and Sweden. However, southern states, such as Georgia, have found that grade too soft. According to Flynn, an FHWA spokesperson said that Georgia might be considering one of the new PG asphalts that were developed under the Strategic Highway Research Program.

[A 1½-column sidebar at the end of the article contains some key points from a conference paper by Marek and Dukatz (Reference 71).]

74. *Fibers Add Muscle to Asphalt Mix Operations*, 1994.

The author of this trade press article is not identified. Of interest is the reporting of equipment development to blow fibers into HMA mixing systems. The article will be of interest to mix designers from the practical viewpoint of how a required quantity of fibers can be metered into the SMA production process. Accompanying the article is an excellent 3-D cut-away drawing, showing delivery of compressed fibers (in packages of 18 kg), into a chamber from which they are transferred by augers into a storage bin. The fluffed fibers can then be metered to the mixing process at the required rate, which is typically 6 lbs (2.7 kg) of fibers per ton of mix.

In describing a project in Indiana, the author indicates that the blow-in fiber chamber could hold 60 m^3. One minor alteration was made to the fiber delivery pipe in the drum mix operation. The 6-inch diameter delivery pipe was angled down at 45° to direct the fibers into the zone where baghouse fines are normally returned. [This is intended to ensure coating of the fibers and to prevent their carry-out in the exhaust gas stream into the dust recovery system.]

75. Polcak, K.D.
Stone Mastic Asphalt Pavement and its Effect on Highway Traffic Noise Levels, 1994.

This study compared the acoustical characteristics of SMA with standard dense-graded HMA at three sites in Frederick County, Maryland. The study demonstrated that SMA has some acoustical benefits. Polcak concludes:

1. Reduction in higher frequency noise with SMA is within the range of perception and greatest sensitivity of the human ear.
2. The macrotexture of SMA may be a partial contributor to the apparent slight increase in the low frequency noise component found in the study, although the data was insufficient to draw firm conclusions. The increase was not significant.
3. The demonstrated acoustical benefits of open-graded plant mix seal, found in previous studies, appear to be maintained with SMA.

[No mix design data are presented in this report.]

76. Stuart, K.D., and Malmquist, P.
Evaluation of Using Different Stabilizers in the U.S. Route 15 (Maryland) Stone Matrix Asphalt (SMA), 1994.

In this detailed account of a laboratory study on SMA, Stuart and Malmquist set out to evaluate the effects of using different additive stabilizers on draindown, rutting, low temperature cracking, aging, and moisture susceptibility. To do this, the authors assembled an impressive array of test methods:

1. DRAINDOWN
   German [Schellenberg -- see Reference 35].
   FHWA 2.36-mm Sieve Test.
   Open-Graded Friction Course (Pie Plate Test).
2. RESISTANCE TO RUTTING
   Georgia Loaded-Wheel Tester (GLWT) at 40.6°C.
   French Pavement Rutting Tester at 60°C.
   Gyratory Testing Machine (GTM) at 60°C.
   Gyratory Static Shear Strength.
   Gyratory Stability Index (GSI).
   Gyratory Elasto-Plastic Index (GEPI).
   Refusal Air Voids Levels
3. RESISTANCE TO LOW TEMPERATURE CRACKING
   Diametral Modulus.
   Indirect Tensile Strength.
   Tensile Strength.
   Tensile Strain at Failure.
   Work to Cause Tensile Failure.
4. RESISTANCE TO AGING (SHRP M-007)
5. RESISTANCE TO MOISTURE DAMAGE
   Tensile Strength Ratio (TSR).
   Diametral Modulus Ratio.
   Percent Visual Stripping.

Mix design and materials information can be summarized as follows:

MIX DESIGN

Design was by 50-blow Marshall, using binder contents in the range of 5.5 to 7.0% by mixture weight in increments of 0.5%. The target mixing and compaction temperatures were 154°C and 143°C respectively.

ASPHALT CEMENT

AC-20 and two modified binders were used. The properties are provided in the paper.

ADDITIVE STABILIZERS

Included in the study were two loose cellulose fibers, a pelletized cellulose fiber, a loose rock wool fiber and two polymers.

AGGREGATES

The aggregates were a blend of two gradations of diabase and a limestone. All three aggregates met or equaled the German test for flat and elongated particles, i.e., not more than 20% having a length to width ratio greater than 3 to 1. The Los Angeles Abrasion value for each aggregate was below 30%.

Texas, Maryland aglime with 100% passing the 12.5 mm sieve and 65% passing the 75µm sieve was stated to be the mineral filler. [The gradation of the passing 75µm material is not given.]

Stuart and Malmquist provide gradations for all materials, including the target blend, actual blend, and an altered blend that was used to evaluate the effect on draindown. The latter two gradations are shown below.

	Percent Passing	
Sieve Size mm	Target Blend	Altered Blend
19.0	100.0	100.0
12.5	91.8	92.0
9.5	74.2	74.0
4.75	33.8	41.0
2.36	18.9	23.0
1.18	15.6	15.9
0.60	14.7	15.3
0.30	14.0	14.4
0.15	13.0	13.2
75µm	10.1	10.1

In their discussion of the results, the authors comment that the optimum binder content with one of the cellulose fibers was only 5.9% (0.6% lower than another loose cellulose fiber, and 0.3% lower than the rock wool fiber). In addition, one of the polymer suppliers' representatives stated that the SMA binder content with the polymer should have been less than the binder content with fibers. It was, in fact 6.5%, i.e., the same as one of the mixtures with cellulose fibers. The authors state that the mix was tested again but the same result was obtained. [Scherocman (Reference 68) discusses problems with binder contents in some detail.]

Among the results, discussions, and conclusions are:

DRAINDOWN

1. The polymer-modified and an AC-20 control mix had the highest amounts of draindown and failed the German and OGFC methods.
2. Altering the gradation significantly reduced the amount of draindown.
3. Discrepancies were encountered in two of the tests -- the Schellenberg and FHWA 2.36 mm tests.

RUTTING, AGE HARDENING, AND LOW TEMPERATURE CRACKING

1. Stabilizing additives had no significant effect on rutting susceptibility even though optimum binder contents varied from 5.9 to 6.5%.
2. Reducing the optimum binder content by altering the gradation increased the susceptibility to age hardening but had no effect on rutting susceptibility and low temperature properties.

MOISTURE DAMAGE

The data indicated little susceptibility to moisture damage. However, the effect of additive stabilizers could not be assessed because anti-stripping additives were used.

77. Carpenter, S.H.
Mix Design Considerations for SMA Mixes, 1994.

Carpenter begins this paper with a philosophical essay in which he traces the development of SMA in Europe with the mixture's characteristic stable stone skeleton. He comments that current design approaches in the U.S. have followed the recipe-type procedures that are used in Europe but he notes in this procedure the lack of validation of stone-on-stone contact in the compacted SMA.

The author then discusses in some detail what he calls some of the critical elements required to achieve SMA. The elements treated by Carpenter are:

1. DRAINDOWN

Carpenter, after describing briefly the Schellenberg Test, says that an accepted procedure for establishing the amount of stabilizing additive is uncertain at present and represents an area for further research. He shows, by plotting changes in penetration and softening point, the effects on the rheological characteristics of an asphalt cement by increasing amounts of cellulose fibers (One domestic and one European). [There is little difference between the fibers in the effects produced.] He also shows the draindown effects of various percentages of two different fibers (again European and domestic) on an AC-20 asphalt cement. The domestic fiber was tested only at the 4% level. At 6.5% asphalt cement content, the domestic fibers appeared to be comparable to the European fibers; at lower asphalt cement contents, the domestic fibers appeared to be slightly better than the European fibers.

2. GRADATION

The author believes that tests on graded aggregate for compatibility of stone and sand sizes are not enough to guarantee a stable stone skeleton. He cites the procedure of compacting the material retained on the #4 sieve by rodding or vibratory hammer to calculate the remaining voids to be filled by the asphalt/sand/filler matrix and the amount of sand (passing #4 sieve) from that space [allowing for asphalt and filler].

3. MIXTURE VOLUMETRICS

Carpenter believes that the two approaches to SMA mix design (fixed asphalt cement content and varied proportions of stone/sand versus varied asphalt cement content and fixed aggregate gradation) can be satisfactory only with verification of stone skeleton development. The author discusses at some length VMA, voids, and compaction of SMA. In a true SMA, he says, there is essentially no densification of the matrix, which contains almost all the voids in the final mix. Thus, he concludes, increasing the asphalt cement content will not alter the compaction characteristics; and, therefore, the only factor altering air voids is the addition of asphalt cement. VMA should be relatively constant. The author cites two cases in Illinois, in one of which a problem developed. In the problem mix, Carpenter illustrates VMA increasing with increasing asphalt cement content, whereas, in the other mix the VMA was virtually stable at between 15.5 and 16% for asphalt cement contents between 6 and 7.5%.

Carpenter believes that the current FHWA gradation should contain more coarse aggregate particles, particularly 9.5 mm material.

4. SAND/STONE RATIO

Adjusting the sand/stone ratio, says the author, should be the primary way to produce an SMA with satisfactory air voids at higher asphalt cement content.

Using diametral resilient modulus for various sand/stone ratios and increasing asphalt cement content mixtures, Carpenter shows a distinct change in the shape of the curves when the sand/stone ratio is about 30/70. However, he concluded that the results did not signify that 74% stone content was better than 70% stone content because the test emphasizes binder properties.

5. STONE-ON-STONE SKELETON

To illustrate the presence of a stone-on-stone skeleton, Carpenter compacted samples at optimum asphalt cement content (3% air voids) using 35, 50, 75, and 110 blows per side with the Marshall hammer.

He notes that for the FHWA gradation, there was very little difference between 50 and 75 blows compaction on diametral resilient modulus results.

6. PARTICLE SHAPE

To illustrate the effect of particle shape on mix design, Carpenter removed all flat and elongated particles from a limestone aggregate, leaving only cubical particles on each sieve size. [The sieve sizes are not identified and the criteria used are not given although the author says that about 20% were elongated but not flat, about 20% were round and flat, about 25% were flat and elongated, and less than 5% had a length to thickness ratio greater than 5:1.] The remaining cubical particles were then blended to meet the FHWA gradation and a mix design was done. Carpenter concluded that the mixture was not significantly different. He notes that the optimum asphalt cement content was the same as for the total aggregate, and the VMA was acceptable [about 16.5 at asphalt cement contents of 6 to 7%].

Among Carpenter's conclusions are the following:

1. The mix design process does not demonstrate long-term stability of the stone skeleton.
2. Reliance on gradation alone will lead to erroneous conclusions.
3. Volumetric curves for SMAs are different from regular [dense-graded] mix design curves.

4. Some means of permanent deformation testing (repeated load or wheel tracking) is needed.

78. Mogawer, W.S. and Stuart, K.D.
Evaluation of Stone Matrix Asphalt Versus Dense-Graded Mixtures, 1994.

Following a brief description of the development of SMA in Europe, Mogawer and Stuart report on a laboratory study, which compared the properties of SMA and dense-graded HMAs in terms of their respective resistances to rutting, moisture damage, low temperature cracking and aging. The study was also intended to determine which mechanical tests could be used to measure the rutting susceptibility of SMAs.

AGGREGATES

Dense-graded HMAs and SMAs with nominal maximum size aggregates of 12.5 mm and 9.5 mm were used (designated D 12.5, SMA 12.5, D 9.5, and SMA 9.5). The aggregate was a crushed diabase and the asphalt cement was AC-20. [Filler type and gradation are not mentioned in the report.] Mogawer and Stuart say that the aggregate and the AC-20 are the same ones used to construct pavement sections tested by the Accelerated Loading Facility (ALF) at the FHWA's Turner-Fairbank highway Research Center. [No references to results from that testing are provided in the report.]

Design gradations and optimum asphalt contents were:

	Percent Passing			
Sieve Size mm	D 12.5	SMA 12.5	D 9.5	SMA 9.5
19.0	100.0	100.0		
12.5	95.0	95.0	100.0	100.0
9.5	82.0	71.0	95.0	95.0
4.75	56.0	25.0	66.0	46.0
2.36	39.0	20.0	48.7	25.0
1.18	29.0	18.0	37.2	20.0
0.60	21.0	16.0	26.9	16.0
0.30	13.8	13.0	16.0	13.0
0.15	9.1	12.0	8.7	12.0
75µm	6.3	10.0	6.7	10.0
Optimum ac %	4.5	6.7 (6.8)[1]	5.2	6.3 (6.5)[1]

[1]AC-20 with polymer.

The SMA aggregate blends meet the gradations previously recommended by Stuart (Reference 35). Mogawer and Stuart say that the SMA 12.5 gradation also meets the ranges recommended by the FHWA's Technical Working Group. [The current recommendations (Reference 81) require not more than 3% passing the 20µm sieve. As the filler gradation is not given in the report, it is not known if the SMA 12.5 mix satisfies that condition.]

ASPHALT CEMENT

AC-20 was used.

STABILIZING ADDITIVE

1. Cellulose pellets (50/50 cellulose fiber and asphalt cement) applied at 0.6% by total weight of mixture.
2. Polymer applied at 7% by weight of the asphalt cement. Polymer-modified SMAs were used only for rutting resistance and drainage potential comparisons.

MIX DESIGN

1. SMAs:
   50-blow Marshall, 3% air voids.
2. Dense-graded mixtures:
   75-blow Marshall, 4% air voids.

TESTS

The authors applied the following tests:

1. Rutting
   - LCPC Pavement Rutting Tester
   - Georgia Loaded Wheel Tester
   - Corps of Engineers Gyratory Testing Machine
   - Unconfined repeated load tests at 40°C on samples compacted to design air voids by kneading compaction. The vertical stress was 0.45 MPa. Two confined repeated load tests were done on the SMA 12.5:
     1) 0.59 MPa vertical stress
        0.14 MPa confining pressure
        0.45 MPa deviator stress.
     2) 0.45 MPa vertical stress
        0.14 MPa confining pressure
        0.31 MPa deviator stress.

2. Moisture Susceptibility
   - Diametral modulus
   - Static indirect tensile strength.

3. Low Temperature Cracking
   - Diametral modulus at -32, -24, -16, -8, 0, 5, 16, 25, 32, and 40°C.

4. Binder Drainage
   - Schellenberg
   - FHWA binder drainage test for open-graded friction courses
   - FHWA 2.36-mm sieve drainage test.

5. Aging - SHRP Method M-007.

Among the results obtained and conclusions reached are:

1. Dense-graded HMAs had higher stabilities and lower flows than SMAs. [This can be expected. The European experience is that Marshall stabilities and flows do not mean much as far as evaluating SMAs for rutting potential is concerned.]
2. The VMAs of each SMA did not vary with binder content. [Carpenter (Reference 77) believes that in a true SMA, the VMA should be relatively constant.]
3. The LCPC rut tester, the Georgia Loaded Wheel Tester, and the Gyratory Testing Machine revealed no significant differences among the mixtures.
   Extraction tests showed that both Marshall and Gyratory compaction fractured the aggregate and altered the gradation of the mixture. Significant increases in the percentages of aggregate passing the 4.75 mm and 2.36 mm sieves were noted. Unexpectedly, unconfined compressive repeated load tests showed that the SMAs had significantly higher average permanent deformations than the dense-graded HMAs. Changing the vertical and confining pressures did not improve the data much for the SMA 12.5 (with cellulose) [no results are given for the polymer-modified SMA 9.5 or SMA 12.5]. [However, although the authors do not mention it in the text, it is worth noting that the voids for the two confined tests were 2.1%.]
   The authors concluded that a test using 101.6 mm by 203.2 mm specimens might not be applicable to SMA.
4. Both SMAs with cellulose fibers had less visual stripping than the dense-graded mixtures.
   The results from tensile strength testing showed that the SMAs were more resistant to moisture damage than dense-graded mixes.
5. There was no significant difference in diametral modulus between the D 9.5 and the SMA 9.5 mixtures. A statistical analysis showed that the stiffnesses of the SMA 12.5 were significantly lower than the D 12.5 mix, implying that SMA will be less susceptible to low temperature cracking.
6. The polymer-modified SMA 12.5 had the highest amount of drainage and failed all three tests. The polymer-modified SMA 9.5 passed.
7. Both the D 12.5 and D 9.5 mixtures exhibited significant increases in dynamic modulus and tensile strength results compared with both SMAs, indicating that the dense-graded mixtures might be more susceptible to cracking after aging than the SMAs.

79. Svec, O.J., and Veizer, R.
Structural Strength of Asphalt Rubber Concrete Developed Through Stone Mastic Asphalt Concept, 1994.

According to the authors, the focus of current research at the Centre for Surface Transportation Technology is to develop a high performance HMA rubber based on the SMA concept. They present the results of a laboratory study on this issue. The following is a summary of the paper:

MATERIALS

The aggregates used were limestone, crusher screenings and natural sand. Anything passing the 90µm sieve was used as the limestone filler. [A hydrometer analysis was done on the filler passing the 75µm sieve but the gradation is not reported. No aggregate tests other than densities and sieve analyses are reported.]

The asphalt cement was 85 - 100 penetration grade.
Cellulose fibers at 0.3% by weight of mix were added.

The selected crumb rubber was produced by cryogenic grinding to the following gradation:

Sieve Size	Percent Passing
#8	100
#10	97
#20	75-97

In addition, the maximum moisture content was 0.75%, rubber hydrocarbon content was between 40 and 50%, and mineral contaminants 0.25% [presumably maximum].

MIX DESIGN

Aggregate gradation followed the German guidelines as follows:

Sieve Size mm	Percent Passing
16	100
11	90-100
8	50-80
5	30-50
2	20-30
90µm	8-13

The asphalt cement content for the control mix with no rubber was 4.6%. Crumb rubber was added at 5% increments up to 20%, based on the weight of asphalt cement.

TESTS

1. Indirect Tensile Test (ITS) (ASTM D 4123).
2. Fatigue. The authors say they used cylindrical specimens in an arrangement identical to the ITS but load controlled, using either 15 or 30% of the static strength determined previously. A compressive Haversine wave of frequency 1 Hz was applied.
3. Uniaxial compression at 25 and 40°C using 690 kPa square wave loading for 0.2 seconds followed by a 1.8-seconds rest period. A minimum load of 5 kg was used during the rest period to avoid impact pressures and separation of the loading head.

RESULTS AND CONCLUSIONS

Among the results and conclusions are:

1. ITS value peaked at 10% crumb rubber content. The mix containing 20% crumb rubber had about the same strength as the control mix.
2. In fatigue, the control samples had the lowest number of cycles to failure while the samples with 20% crumb rubber had the highest cycles.
3. At 25°C, the 5% crumb rubber content samples had the lowest permanent axial strain. This was closely followed by the 10% crumb rubber sample. The control mix had the highest strain.

At 40°C, there was little difference in permanent strain between the 5% and 10% crumb rubber mixes after almost 4,500 cycles. The control mix failed before 2,000 cycles. Because of time constraints, the 15% and 20% crumb rubber mixes were tested only to 2,000 cycles at which point their respective permanent strains were greater than both the 5% and the 10% crumb rubber mixes after 2,000 cycles.

80. Shelton, M.
Stone Mastic Asphalt, Route I-70, Callaway County, Construction Phase Report, 1994.

Reporting on an experimental 1¾-inch SMA overlay in 1993, Shelton says that the project was the first SMA to be produced through a drum mixer in Missouri. It was also the first SMA in Missouri in which a limestone-steel slag rather than a limestone-porphyry was used.

The specification for materials is contained in an appendix to the report. From the appendix and the body of the report, the following main points may be noted:

AGGREGATES

1. Los Angeles Abrasion (AASHTO T 96) $\ngtr$ 35%.
2. Flat and elongated particles (ASTM D 4791) for material retained on the #4 sieve not to exceed 20% (3:1 ratio) nor 5% (5:1 ratio).
3. 100% of particles retained on the #4 sieve shall have at least one fractured face and at least 75% shall have two or more fractured faces.
4. Sodium sulfate soundness loss (AASHTO T 104) $\ngtr$ 15% at 5 cycles.
5. Absorption (AASHTO T 85) $\ngtr$ 4%.
6. Fine aggregate is 100% manufactured sand with 70 - 100% passing the #4 sieve. Liquid limit (AASHTO T 89) $\ngtr$ 25.
7. Portland cement is not allowed as mineral filler. [What is allowed is not clear from the report. The reader is referred to Sec 1002.3 of the Missouri Standard Specifications for Highway Construction. This indicates that mineral filler can be limestone dust, Portland cement, or other suitable mineral filler. The allowable gradation is shown in brackets below.] The gradation of the mineral filler used was:

Sieve Size	Percent Passing
#30	100.0 (100)
#50	99.5 (95-100)
#100	96.0 (90-100)
#200	78.0 (70-100)

8. Hydrated lime is not required.

STABILIZING ADDITIVES

Three sources for cellulose fibers, and one source for mineral fibers are given in the appendix. Pelletized fibers were allowed for drum mix operations.

ASPHALT CEMENT

The Schellenberg draindown test is specified for the AC-20 grade used.

MIX DESIGN

1. Marshall compaction 50 blows.
2. Air voids, percent 3-5 [The previous range (1992) given in Reference 63 was 3-4%.]
3. Stability 1400 lbs. min. [Not mentioned in previous report.]
4. Flow (1/100 in) 15 max. [Previously 8-15.]
5. VMA, percent 17 min. [Previously 16.]
6. VFA, percent 78 min. [Same as previous.]
7. The design gradation range is shown below. For comparison, the JMF gradations for the current project and the 1992 project are also shown.

		Percent Passing	
Sieve Size	Design Range 1993	JMF 1993	JMF 1992
¾ in	100	100	100
½ in	85-100	87.5	97.9
⅜ in	60-75	69.8	70.4
#4	25-34	26.6	33.9
#8	18-24	18.1	18.5
#16	14-20	15.1	14.6
#30	12-17	13.6	13.7
#50	10-15	12.4	13.3
#100	9-13	11.3	12.7
#200	8-12	8.9	10.1

8. The final mix had the following characteristics:

Mineral aggregate	93.2%
Fibers	0.3%
AC-20	6.5%
Voids	3.91%
Stability	1539 lbs.
VMA	20.11%
VFA	80.6%
Passing #200:AC-20	1.3

71. *Guidelines for Materials, Production, and Placement of Stone Matrix Asphalt (SMA)*, 1994.

This document is a consensus of an FHWA Technical Working Group and represents the current thinking of the group on the best approaches to specifying SMA. There is much useful and important information in the guidelines. The following represents a brief summary of significant parts. [For specification purposes, readers should refer to the complete current edition of the document.]

SMA MIX REQUIREMENTS

50-blow Marshall design (AASHTO T 245)	
VTM % (AASHTO T 166, T 209, T 269)	3-4.
Asphalt Content % by weight of mix	6.0 min.
VMA % (TAI MS-2)	17 min.
Marshall Stability N (lbs.)	6200 (1400) suggested minimum.
Flow 0.25 mm (0.01 in.)	8-16.
Draindown (NCAT Draindown Test) %	0.3 max. (1 hr. reading).

Footnotes in this section refer the reader to a later section called "Notes to the Engineer." Relative to Marshall Stability, the notes say:

"Values may be modified depending on other SMA mix considerations. Measurements are for information and should not be the sole reason to accept/reject an SMA design."

AGGREGATE

Coarse aggregate (AASHTO M 283 for Class A aggregates):	
Los Angeles Abrasion (AASHTO T 96)	30% max.
Flat and Elongated Particles (ASTM D 4791)	
(measured on material retained above the 4.74 mm sieve)	
Length to width 3 to 1 basis	20% max.
Length to width 5 to 1 basis	5% max.
Sodium sulfate soundness loss (AASHTO T 104)	
5 cycles	15% max.
(If magnesium sulfate used	20% max.)
Particles retained on the 4.75 mm sieve:	
One fractured face	100% min.
Two fractured faces	90% min.
Absorption (AASHTO T 85)	2% max.
Coarse and fine durability index (AASHTO T 210)	40 min.

Relatively pure carbonate aggregates or aggregates that are known to polish should not be used.

Fine aggregate (AASHTO M 29):

100% crushed, manufactured sand.

Sodium sulfate soundness loss (AASHTO T 104)
5 cycles 15% max.
Liquid limit (AASHTO T 89) 25 max.

GRADATION

Sieve Size	Percent Passing
19.0 mm (¾ in.)	100
12.5 mm (½ in.)	85-95
9.5 mm (⅜ in.)	75 max.
4.75 mm (#4)	20-28
2.36 mm (#8)	16-24
600µm (#30)	12-16
300µm (#50)	12-15
75µm (#200)	8-10
20µm	< 3

ASPHALT CEMENT

The guideline specifies AASHTO M 226 and requires mixing at a viscosity of 170 ± 20 centistokes and not more than 177°C.

MINERAL FILLER

Mineral filler is specified as finely divided mineral matter (Rock, limestone dust etc.,) meeting AASHTO M 17. The gradation of commercial filler is limited as in the table above to having less than 20% of its weight less than 20µm in size.

ADDITIVE STABILIZER

Cellulose or mineral fibers are specified at:
0.3% by weight of total mix for cellulose fiber, and
0.4% by weight of total mix for mineral fiber.

Tolerance is ± 10% of required fiber weight.

In the "Notes to Engineers" section, polymer stabilizers are discussed. The group notes that polymer-modified SMAs typically have 0.5 to 1.0% less asphalt cement than comparable fiber-stabilized SMAs. The recommendation is that the appropriate polymer manufacturer should be consulted because the usual SMA guidelines will not be applicable to unique [polymer] stabilizers.

The guideline contains two pages of very detailed properties for cellulose and mineral fibers. These are stated to be under development. [Presumably these detailed properties are intended to help users by defining the properties of fibers that have been used in SMAs.]

The remainder of the guideline is devoted to mixing, hauling, paving, and compaction operations. Considerable attention is given to fiber introduction, with almost two pages in the "Notes to Engineers" section dealing exclusively with the subject. This section covers manual and automated feeding of bulk fiber into batch mixers, and automated metering of bulk and pelletized fiber into drum mixers.

82. Harvey, J., Monismith, C., and Sousa, J.
An Investigation of Field- and Laboratory-Compacted Asphalt-Rubber, SMA, Recycled and Conventional Asphalt-Concrete Mixes Using SHRP Project A-003A Equipment, 1994.

Noting that different laboratory compaction methods have a long history of producing specimens of different resistances to permanent deformation, the authors set out to find out which laboratory compaction method is most similar to field compaction. The laboratory methods selected were Texas gyratory, rolling wheel, kneading, SHRP gyratory, and Marshall.

Among the projects were two that the authors classify as SMAs. These were two sections on I-40, about 35 km east of Barstow, California in the Mojave desert. They were special pavement sections (SPS 521 and SPS 522). The SMAs were 45 mm thick. The materials were placed in April 1992 and cored in September of the same year.

HMA in the field was collected in front of the paver [from which the reader will deduce that the HMA was windrowed] and compacted in the laboratory at the temperature measured [in the hot placed mat before compaction] behind the paver.

Mix design, material type and quality information are not in abundance in this paper. SPS 521 was an AR 4000 asphalt rubber binder mix that may not qualify as a proper SMA. SPS 522 was an AR 4000 polymer-modified SMA. Average gradations are given as follows:

Sieve Size mm	Percent Passing SPS 521 Asphalt Rubber	 SPS 522 Polyolefin
25	100	-
19	99	100
9.5	75	68
4.75	28	30
2.36	22	21
0.60	13	14
75µm	4	10
Binder Content by weight of aggregate	6.8%	5.6%

The SPS 521 mix had air voids between 9.5 and 16.5% while the SPS 522 had air voids between 10.6 and 13.8%.

83. Bukowski, J.R.
SMA -- Innovation in Asphalt Pavement, 1994.

Bukowski provides an updated review of SMA development in Europe, its general principles, and the technology transfer to the U.S. in 1991. From 10,000 tons in that first year, Bukowski says that the figure grew to more than 500,000 tons in 1993.

For the reader who may be unfamiliar with SMA, the author gives a short series of explanations of the important features, such as: gap-grading; 100% crushed aggregate of generally cubical aspect providing a stone-on-stone contact; and a stabilizing mortar of asphalt cement and filler to fill the voids between the coarse aggregate. Bukowski alerts the reader to the use of asphalt cement contents of 6.5 to 7.0% in Europe with 3% voids in the mix. Such levels of asphalt cement, says the author, are much higher than typical mixes in the U.S.

The initial findings from the nearly 50 SMA projects that have been constructed in the U.S. in the last three years are outlined by the author. For SMAs, the amount of sand (less than 4.75 mm size) is about half what is used in conventional mixes and the mineral dust (75μm or less in size) is about two or three times the amounts normally expected. Bukowski points out that the high asphalt cement contents in SMAs in Europe require stabilizer additives, particularly cellulose and mineral fibers. He says that domestic sources of fibers have been developed and that polymer-modified asphalts have become common in state projects.

Bukowski intimates that during 1994, FHWA will conduct a formal evaluation of the condition and performance of existing SMA projects.

84. Brown, E.R., and Mallick, R.B.
Stone Matrix Asphalt-Properties Related to Mixture Design, 1994.

In this project, Brown and Mallick address several important aspects of SMAs, most of which have not been studied previously. These are:

1. Evaluation of the variability in VMA, theoretical maximum density, and optimum asphalt cement contents for SMA between different laboratories.
2. Development of a quantitative method of draindown that is related to measured draindown in the field.
3. Comparison of densities obtained with a gyratory compaction device with the densities obtained using a Marshall hammer.
4. Development of a method to determine if stone-on-stone contact in SMA exists. [Carpenter (Reference 77) also addresses this issue.]

Variability was examined through two round robin series of testing using limestone and Virginia traprock aggregates with American cellulose fibers, AC-20 asphalt cement, and 50-blow Marshall compaction. The filler was agricultural lime [no gradation is provided]. Mixes were made at asphalt contents in increments of 0.5%, giving a range of values above and below the optimum.

In another part of the study, a draindown test was developed and evaluated in the second round robin testing. A brief description of the test is provided in the report. [A slightly more detailed version appears in Reference 81.]

The aggregate gradations used for the above round robin (RR) tests were:

Percent Passing

Sieve Size	RR 1 Limestone	RR 2 Traprock	Draindown Mix A	Draindown Mix B	Draindown Mix C
¾ in.	100	100.0	100.0	100.0	100.0
½ in.	100	84.9	100.0	100.0	100.0
⅜ in.	65	64.2	75.0	65.0	60.0
#4	28	26.8	50.0	30.0	20.0
#8	24	14.3	39.9	24.9	17.5
#16	20	12.0	34.3	22.1	16.1
#30	17	11.7	30.0	20.0	15.0
#50	14	11.2	21.5	17.0	14.8
#100	12	10.3	15.1	13.9	13.3
#200	10	8.5	10.0	10.0	10.0

For the draindown tests, the materials used were:

Gravel and limestone aggregates,
Two kinds of fibers and one polymer at two different proportions,
Baghouse fines and a marble filler.

Comparison of 50-blow Marshall and gyratory compaction was done with a blend of gravel and limestone aggregates. European cellulose fiber was added at 0.3% by weight of total mix. Optimum asphalt cement content was selected at 3% air voids. The number of gyratory machine revolutions required to produce 3% air voids was determined from graphs of air voids versus revolutions. The aggregate gradation used was:

Sieve Size	Percent Passing
½ in.	100.0
⅜ in.	62.5
#4	25.0
#8	21.2
#16	19.1
#30	17.5
#50	15.9
#100	13.6
#200	10.0

Gravel and limestone aggregate blends were also used to evaluate ways of determining if stone-on-stone contact has been achieved. Mixes with 15, 20, 30, 40, and 50% passing the #4 sieve were prepared along with a dense-graded mix with 66% passing the #4 sieve for comparison. For the SMAs, the filler was agricultural lime, European cellulose fiber at 0.3% was added, 50-blow Marshall was used, and the optimum asphalt cement content was taken at 3% voids. VMAs, and voids in coarse aggregates (VCAs) were calculated from compacted samples. To measure VCA with no fine aggregates added, a dry rodded method (ASTM C29) was used. Brown and Mallick say that the VCA in the dry rodded condition represents a state of stone-on-stone contact. The authors then graphed VMA and VCA against the percent fines and compared this plot with the VCA of a mix without any fine aggregates. The belief is that stone-on-stone contact exists when the mix VCA equals the VCA in the dry rodded condition.

Dynamic creep tests were done on a number of mixes with different percentages passing the #4 sieve. A dense-graded mix with asphalt cement content at 5.1% was used for comparison. [Test temperature is not stated.]

The results of the study may be summarized as follows:

1. Variability:

   Optimum asphalt cement content in SMAs is significantly greater than in dense-graded mixes.

Variabilities in theoretical maximum specific gravity and VMA are about the same for SMAs and dense-graded mixes. However, the authors note that SMA mixture quality is not affected as much as dense-graded mixes by changes in asphalt cement content.

2. Draindown:

   Draindown tests were done at 300°F. Brown and Mallick believe that the test temperature should be the expected field temperature. [Presumably the authors mean the mix silo storage temperature or the plant-produced mix temperature when loading directly to trucks.] The type and amount of stabilizing additive significantly affects draindown. In the study, the authors found mineral and cellulose fibers at 0.3% gave the least draindown while mixtures with no additive and 0.3% polymer gave the most. SMAs with baghouse fines had less draindown than mixes with marble dust as filler. Brown and Mallick believe this is attributable to the greater number of smaller particles in baghouse fines and conclude that the distribution of the material passing the #200 sieve must be controlled to prevent draindown problems. They recommend this area for further research.

3. Correlation of Marshall and Gyratory Compaction:

   Based on the data obtained, the authors believe that 90 revolutions of the Corps of Engineers Gyratory Testing Machine (GTM) is a reasonable equivalent to 50 blows of mechanical Marshall compaction. However, the authors say that at present, the GTM should be used for research purposes only while mix designs should be done with the Marshall hammer.

4. Stone-on-Stone Contact:

   Brown and Mallick found that plots of VMA and VCA could be used to identify if a stone-on-stone condition exists and that the dry rodded test appeared to be an easy way to determine the necessary VCA. In their work, they found the condition occurring at around 30% passing the #4 sieve.

5. Evaluation of Creep Properties:

   While noting that the dynamic creep test has been used for some time with good results at NCAT and other laboratories to indicate rutting potential, the authors found higher strain values and lower creep modulus values for both gravel and limestone SMAs compared with the corresponding dense-graded mixes. They note that these findings are contrary to observed field performance. Brown and Mallick suggest that the apparently anomalous results could be because the mixtures were evaluated only at optimum asphalt cement content. They feel that comparing SMA and dense-graded mixes over a range of asphalt cement contents would demonstrate SMAs advantages.

85. *Stone Matrix Asphalt Construction Procedures*, (Draft) 1994.

[The document reviewed is Draft Version 1.2 dated May 1994.]

This is a companion paper to Reference 81 and also represents a consensus of the FHWA's Technical Working Group. As it is a construction document, there is little in it that is directly related to mix design. However, some points are worth noting from a reading of the paper:

1. There is a useful overview of SMA principles and its use as a rut-resisting mix.
2. No serious effort has been made to describe sound construction practices for SMA.
3. Coarse aggregate is usually about 65% or more of the blended aggregates. Stockpile control is essential.
4. SMAs are sensitive to filler content, which are about 5% or more. [Reference 81 shows 8 to 10% passing 75µm, part of which will be from the fine aggregate fraction.]
5. Inaccurate weighing of the mineral filler at mix facilities has caused problems because of the insensitivity of scales on batch plants.
6. AC-20 is the grade of choice for most SMA projects in the U.S. However, for warmer climates a higher viscosity grade may be desirable.
7. Handling, storage and metering of asphalt cement are the same as for standard grades with the exception of polymer-modified asphalt cements for which storage temperatures may change.
8. SMA mixtures are sensitive to asphalt content. [Possibly the group means that there is more variability in SMA optimum asphalt cement contents than in dense-graded mixes. That is what Brown and Mallick (Reference 84) found in their round robin studies. They also noted that SMA mixture quality is not affected as much as dense-graded mixes by changes in asphalt cement content.]
9. Bulk and pelletized fibers have been used in drum and batch mixers.
10. Additive stabilizers may hinder the extraction of binder process during testing of mixes. Some experimentation may be needed to find the best method of extraction.
11. When asphalt modifiers are added at the mixing plant, advice and assistance should be sought from the modifier supplier.
12. The group says it is important that all the feed systems of the plant be carefully calibrated before producing SMA. Again the group comments that

"... any small changes in the amount of asphalt cement can have a major impact on the quality of the finished SMA." [See 8 above.]

13. Typical mixing temperatures are 290-310°F. Production temperatures below 300°F are rare.
14. In a batch plant, wet and dry mixing cycles may need to be increased from 5 to 15 seconds each over conventional mixtures. When pelletized fibers are used in drum mixers, the asphalt cement injection point may be relocated to allow for complete mixing of the pellets before the asphalt cement is added.
15. Do not store SMA overnight, nor at elevated temperatures. A few hours of storage has not been detrimental in U.S. experience.
16. Normal placing temperature for SMA is about 280 to 300°F -- slightly higher if it is a polymer-modified SMA.
17. Keep paver augers turning 85 to 90% of the time to ensure slow auger revolutions. High auger speeds can shear the mortar from the coarse aggregate and lead to fat spots in the finished pavement.
18. Minimize hand work. SMAs are known to be very sticky behind the paver.
19. SMA rolldown is normally 10 to 15% of lift [placement] thickness, i.e., about half the rolldown of conventional HMAs.
20. Vibratory rollers have been used but caution is needed to avoid fracturing aggregates and flushing mortar to the surface.
21. Pneumatic-tired rollers are not recommended.
22. For SMA in-place densities, the nuclear gauge is not as accurate as it is with conventional HMAs. Periodic calibrations with cores from the SMA pavement are recommended.

86. Fujita, D.
Unpublished Report, Watanabe-Gumi Co., Ltd., 1994.

Fujita, in an unpublished report, indicates that SMAs are used in Japan. In September 1992, an SMA (designated W-Mastic Asphalt type 1, having top size aggregate 13 mm) was placed on a steel bridge deck at Bijogi Junction in Tokyo. In November 1993, a thin SMA (designated W-Mastic type 2, having top size aggregate 5 mm) was used for the rehabilitation of a severely rutted pavement in a tunnel 600 km north of Tokyo. The gradations for these two types of SMA are:

	Percent Passing	
Sieve Size mm	W-Mastic Type 1	W-Mastic Type 2
19	100	100
13.2	95-100	100
10	-	100
4.75	30-40	90-100
2.36	20-35	30-40
0.6	15-26	-
0.3	12-22	-
0.15	9-18	10-20
75µm	8-15	8-15

[The above gradations are close to the German gradations (References 10, 36) although the sieve sizes are not exactly comparable.]

ASPHALT CEMENT

The grade used is normally 60-70 penetration.

STABILIZER ADDITIVE

A cellulose fiber is added at 0.3% by weight, with dry mixing for 10 to 15 seconds followed by 40 to 50 seconds wet mixing at a temperature not more than 180°C.

MODIFIER

A proprietary polymer, composed mainly of an emulsified chloroprene, is added at 3% by weight of net component.

MIX DESIGN

Marshall is used. [No details provided but stabilities are measured and are apparently slightly less than dense-graded HMAs.]

Also measured are strain in a bending beam fracture test and a dynamic stability in a wheel-tracking test. [Test details are not provided but results given in the report indicate that the Type 1 SMA appears to be far superior to dense-graded HMA.]

87. Harris, B. M. Stuart, K. D.
Analysis of Mineral Fillers and Mastics Used in Stone Matrix Asphalt, 1995.

This paper presents the results of a laboratory study carried out to develop reliable procedures for characterizing mineral filler and to evaluate the relationship between reported field performances of mineral fillers and laboratory measured mineral filler properties.

Twenty nine different types of mineral fillers, all with 100 percent passing the 150 µm sieve, were obtained: eleven from USA, and eighteen from Sweden, Germany, and Switzerland.

Based on the effect of the fillers on stiffness of the mix, the European fillers were classified as "good" or "bad". Both high and low stiffness are undesirable since the former can lead to cracking and low workability, and the latter can lead to bleeding or shoving. The eleven fillers obtained from U.S.A. were used for developing methodologies for sampling and gradation analysis.

A quartering and rifling procedure is presented in the paper for obtaining representative samples of mineral fillers for testing purposes. A 1 kg (2.2 lb) sample of minus 150 µm material is recommended as the starting point for quartering and sampling. Differences between dry and wash sieving for separating minus 150 -µm material from coarser fractions is presented in the appendix.

Some difficulties and error possibilities are discussed regarding analysis of particle size distribution by laser diffraction procedure is discussed. It is mentioned that ultrasonic agitation of particles can lead to breakdown of particles in addition to separation of conglomerates, retaining and drying all the material passing through the sieves becomes increasingly difficult with addition of sieves, and that the effectiveness of washing the material over the screen is difficult to control because of test and operator variability.

Three test parameters were evaluated to achieve acceptable and reliable particle size distribution results with the HORIBA LA-500 particle analyzer. The parameters were: number of samples needed, minimum number of testing replicates per sample, and acceptable levels of agitation. With different levels for each of the parameters, a total of 180 tests were conducted for each minus 150 µm aggregate. The authors used nine parameters for characterizing the gradation results. The two minute agitation time was found to be the best and is recommended by the authors. An increase in agitation time was found to cause an increase in variability of the parameters and hence a decrease in the precision.

The measured properties from the fillers included gradation properties, Anderson Rigden Voids, and Stiffening Power, based on the Ring-and Ball Softening Point of a mastic compared to the softening point of the neat binder alone. The measured properties were then correlated to reported performance of each filler for use in SMA and HMA mixtures. Scatter plots revealed no definite relation between performance and any of the measured properties. However, the authors hypothesized that filler with more than approximately 80 percent passing the 20 µm sieve would most likely be unacceptable for use in SMA or HMA mixtures. Anderson Rigden void values were found to be capable of predicting performance of fillers. The authors mention that a range of 34 to 39 percent voids in a compacted sample can be designated as good filler region. A multi-variable model is then presented, with performance of filler as the dependent variable, and six measured properties: Anderson Rigden Voids, Stiffening Power at 35 percent filler by volume, absolute value of the difference between two different measures of the skewness of the particle size distribution, Coefficient of Uniformity, Fineness Modulus, and Specific Surface Area. A better fit of the data was obtained with a non-linear logistic regression model with all the six mix parameters. An alternate full non-linear model containing Anderson Rigden Voids, Stiffening Power at 35 percent filler by volume, absolute value of the difference between two different measures of the skewness of the particle size distribution, and the coefficient of Uniformity, was found to be able to correctly identify all the fillers as good or bad. The concept of Stiffening Power, applied through Ring-and-Ball and DSR measurements, failed to characterize the fillers as good or bad. Comparison of the two types of measurements did not show any kind of relationship.

The following conclusions are made at the end of the study:

1. The washed sieve portion of the minus 150 µm fraction, after the dry sieved minus 150 µm material is removed, is much finer than the dry sieved minus 150 µm material alone. The authors recommend the use of the total minus 150 µm fraction to be included the analysis.
2. Procedures mentioned in the paper are recommended for voiding breakdown of mineral fillers with high clay content during ultrasonic agitation.
3. The Anderson Rigden Voids was the only independent variable capable of characterizing “good” and “bad” fillers.
4. A full non-linear regression model containing Anderson Rigden Voids, absolute value of the difference between two measures of the skewness of the particle size distribution, Coefficient of uniformity, Fineness Modulus, and Specific Surface Area, and an

alternate-full non-linear regression model containing Anderson Rigden Voids, Stiffening Power at 35 percent filler by volume, absolute value of the difference between two measures of the skewness of the of the particle size distribution, and Coefficient of Uniformity, were fond to be the two best models for characterizing “good” and “bad” fillers.

5. No correlations were found between the Stiffening Power obtained by the Softening Point (Ring-and-ball) method and the DSR method.

88. Partl, M. N., Vinison, T. S., R. Hicks, G. R., and Younger, K.
Performance-Related Testing of Stone Mastic Asphalt, 1995.

This paper presents the results of a study carried out to apply selected Strategic Highway Resrahc Program (SHRP) tests and aging conditioning methods to Stone Matrix Asphalt (SMA) mixtures and to evaluate the influence of several material parameters which were considered to be significant. The influence of long-term oven aging (LTOA), low temperature cracking, resilient modulus, rutting, and water sensitivity of SMA mixtures were evaluated. The different test methods included thermal stress restrained specimen test (TSRST), the indirect tensile test (IDT), the constant height repetitive simple shear test (CHRSST), the Environmental Conditioning System (ECS), and the Laboratoire Centrale des Ponts et Chaussees (LCPC) wheel tracking device. Two types of SMA were investigated: slabs from a road in Switzerland, and laboratory samples produced with two extreme air void contents using the same aggregate gradation as the Swiss SMA.

The Swiss SMA had a maximum aggregate size of 11 mm (0.43 inch) and was taken as 400 x 400 mm (15.8 inch x 15.8 inch) field slabs from a fresh 35 mm (1.4 inch) thick surface course placed in 1993. The mixture contained a 6.7 percent of B80/100 (penetration-graded) asphalt cement, and 0.8 percent of natural asphalt with fibers NAF 501. The authors mention that the air void content of the mixture was 13 volume percent, and that about 5 volume percent of the total air void content was due to the open surface texture of the SMA. The authors also mention the sampling of a high performance, zero air-void mastic-type material, GA, from a bridge deck. The binder content for this material was 6.5 percent.

The laboratory prepared SMA mixture was produced with a kneading and a roller compactor, with a binder content of 7 percent. A cellulose fiber content of 0.35 percent was used for the mixtures.

The TSRST results showed that six of the fourteen SMA specimens tested displayed a drop in stress without a clear fracture, and that all the laboratory SMA specimens failed by fracture, and as with the field sample, some aggregate was observed in the fracture surface of the specimen.

The results from CHRSST tests showed that the shear phase angle decreased as the frequency decreased, and at low frequencies as temperature increased. The authors conclude that these effect show that SMA behaves like a viscoelastic solid and thus may behave differently when compared to dense graded HMA due to difference in structure.

The LCPC tested specimens were found to deform laterally, and had visible shear flow zones under the wheel track. The authors indicate that this shows that an aggregate skeleton without sufficient lateral confinement and interlocking becomes unstable and tends to shove.

During the ECS tests, the laboratory prepared SMA specimens with lower air voids were found to be practically impermeable over the duration of the test. However, after testing and splitting, water was found in the center of all the specimens. The specimens with 4.8 percent air voids showed no stripping, whereas those with higher air void contents showed some stripping.

The authors conclude that because of the coarse aggregate skeleton, evaluation of SMA will need modifications to conventional laboratory test procedures.

89. West, R. C., and Ruth, B. E.
Compaction and Shear Strength Testing of Stone Matrix Asphalt Mixtures in the Gyratory Testing Machine, 1995.

This paper reports the results from a laboratory compaction and characterization study of Stone Matrix Asphalt mixtures. Eleven SMA mixtures were compacted in the laboratory with a Corps of Engineers gyratory testing machine (GTM) with an air roller to simulate initial construction and traffic densification. The authors mention that with the air roller the strain applied to a stable mix would decrease with increase in shear strength of the mix, whereas the strain would increase with loss in shear strength in the case of a low strength mix. The average aggregate gradation and binder content data obtained from field construction records were used as target values for the laboratory compacted mixtures. Two sets of samples were prepared for each of the mixes: one set was compacted to achieve average initial in-place density, and another set was compacted to 300 revolutions or shear failure to simulate traffic induced densification.

Materials used in the study included aggregates, mineral fillers, stabilizing additives, anti-stripping additives, and asphalt cement or modified binder for eleven SMA mixtures used by highway agencies and paving contractors. The authors provide gradation results from field material for each of the mixes. For all the mixes the amount of material passing the 19.5 mm (3/4 inch) sieve was 100 percent. Stabilizers used in the mixes included Novophalt and Inorphil in three projects, Vestoplast in three projects, Styrelf and Cellulose in one project, Inorganic fiber in one project, Parma-Tac and Arbocel in one project and only Arbocel in one project. No stabilizer is mentioned for one mix. Three of the mixtures used AC-30, another three used 85-100 penetration grade asphalt cement, two mixtures used AC-20, one used AC-20 Sp., and another used a MAC 10 asphalt cement. The asphalt cement grade for one mix is not mentioned. AgLime was used in two of the mixes. The percentage of material passing the 4.75 mm (No. 4) sieve ranged from 28 to 45. The asphalt content varied between 5.5 and 6.7 percent.

Three samples from each of the mixes were compacted at 12, 15 and 18 gyrations to develop curves of gyration versus densification. To obtain a standard compactive effort required by the mixes to achieve initial in-place density, an Analysis of Variance was conducted with the compaction results from a Model 6B/4C GTM, and the following parameters were chosen for best results:

initial air roller pressure: 62 kPa (9 psi)
ram pressure: 690 kPa (100 psi)
initial angle of gyration: 0.052 radian (3 degree)
Number of gyration: 12

Using the above settings, three compacted samples from each set were further compacted to 300 revolutions to obtain gyration versus shear strength and gyration versus densification plots. Values of percent of maximum density and shear strength at different gyrations are presented for the different mixes. Several types of responses were observed from the results: increase in shear strength with increase in density, decline in shear strength with increase in density, and stable shear strength with densification. The authors indicate that in general most of the mixes had excellent shear strength. To evaluate the rutting susceptibility of mixes, the gyratory shear strength and density of the mixes at 200 gyrations were determined. Three of the eleven mixes showed shear strength less than the critical value of 372 kPa (54 psi) obtained from correlation with Hveem stability. It was found that at 200 gyrations most of the mixtures had densified to void content of 2 to 3 percent. The authors mention that the mixtures with low air void contents did not exhibit loss of shear strength. This indicated that SMA mixtures were less sensitive to low air void contents.

The authors conclude that compaction of SMA for design and testing can be accomplished by the Corps of Engineers GTM with an air roller, and that the GTM is sensitive to the shear strength characteristics of SMA mixtures. The authors expect that if the shear strength parameter serves as a good indicator rutting it may be used in future to optimize mix design for SMA mixtures.

90. Brown, E. R., Haddock, J. E., and Crawford, C.
An Investigation of Stone Matrix Asphalt Mortars, 1996.

This paper summarizes the results obtained from laboratory characterization of mortars used in Stone Matrix Asphalt. The objective of the study was determine the feasibility of using the Superpave testing system for SMA mortar characterization, and to evaluate the effect of mortar components on mortar performance. The authors classified the mortar into two categories: total mortar consisting of the aggregate passing the 2.36 mm (No. 8) sieve, mineral filler, stabilizing additive, and asphalt cement, and fine mortar consisting of the portion of aggregate passing the 0.075 mm (No. 200) sieve, stabilizing additive, and asphalt cement. The total mortar fraction was tested as a mixture, and the fine mortar fraction was tested as a binder.

In the literature review the authors mention the different definitions and types of fillers and fibers used in SMA. Several references on tests for measuring draindown potential of SMA mixes are also mentioned.

The fine mortar fraction was tested in the Dynamic Shear Rheometer under original, RTFOT and PAV conditions and in the Direct Tension (DT) and Bending Beam Rheometer (BBR) under PAV conditions. Testing of the original material was also conducted in the Brookefield Viscometer (BV). The test temperatures were based on Superpave guidance for Auburn, Alabama. The total mortar was tested at low, intermediate, and high temperatures using the BBR, Resilient Modulus (RM), Indirect Tensile Test (ITT), and BV. The low and high temperatures were determined according to Superpave system for Auburn, Alabama.

TEST MATERIALS

One virgin asphalt cement, three modified asphalt cements, two mineral fillers, and three types of fibers were used in the study. The five aggregate types included traprock, granite, limestone, Florida limestone, and siliceous gravel. The authors indicate that granite was chosen as the fine aggregate in this study since it has properties representative of fine aggregates typically used in SMA.

An AC-20 and three modified AC-20 asphalt cements were used in the study. The modifiers included Styrene-Butadiene-Styrene (SBS), Styrene-Butadiene-Rubber (SBR) and Polyolefin.

The fibers selected for the study included cellulose, rock wool, and slag wool.

RESULTS

Fine Mortar

The phase angle, δ, obtained from DSR testing of the fine mortar, was 80 degrees or above for all the binders, except one, which had a δ value in the range of 60 to 70 degrees. The authors indicate that the δ value seems to be the discriminating measure of the elastic component of the asphalt cement properties even when other additives such as fibers and fillers are added. None of the additives affected the slope, m, value.

When tested in the DSR at 64ºC and the BBR at -12ºC, the binders were found to be stiffened more by the baghouse fines than by the limestone dust. At TFO and PAV conditions, both the fillers stiffened the binders equally.

In general the fibers did not have any stiffening effect on the binders. Of the three different types of modifiers used, the SBS modifier stiffened the binder more than the others. The strain value for asphalt cement containing SBS was also found to be different than the strain value of the asphalt cements with the other modifiers.

All of the mortars were found to be stiff for testing in the Brookfield Viscometer at the Superpave designated temperature of 135ºC (275ºF).

The authors indicate that the DSR was found to be a suitable test method for the fine mortars, even though some difficulty was encountered in specimen molding. A higher test temperature was required to avoid the error due to the incorporation of air voids into the samples, especially with higher viscosity.

Neither the Rolling Thin Film Oven Test (RTFOT) nor the Thin Film Oven Test (TFOT) was found to be suitable for testing of the fine mortar. In the RTFOT testing the material "climbed" out of the bottles, and in TFOT testing the material formed a separate crust at the bottom of the pans.

The Pressure Aging Vessel (PAV) temperature of 100ºC (212ºF) was not high enough to produce the film thickness required by the Superpave for the stiffer mortars.

In the Bending Beam Rheometer tests sample preparation was the major problem. The molds had to be heated, and some of the stiffer mortars were “rodded” into the molds to prevent air voids in the samples.

Molding the specimens without the introduction of air voids was the major problem in the Direct Tension Test (DTT). In many cases the specimens failed at the interface between the asphalt and the end pieces.

Total Mortar

The total mortar was prepared by hand with granite fine aggregates and either limestone dust or baghouse fines for mineral filler.

The baghouse fines were found to have a greater stiffening effect on the binders than the limestone dust, irrespective of the modifier used. The baghouse dust also decreased the “m” value for the mortar with virgin asphalt cement, whereas the limestone dust increased the “m” value for both neat asphalt cement and the SBS modified mortar. The SBS modified mortar was also found to be less stiff at the low temperature than the virgin mortar. The cellulose and slag wool fibers were found to have no stiffening effect on the total mortar.

The total mortar was found to be too stiff to allow testing in the Brookfield Viscometer at the Superpave designated temperature.

For the BBR tests, the mortars had to “packed” to avoid air voids, and the authors comment that BBR is a viable test method if one could mold the beams. The increase in specific gravity over that of asphalt cement caused the beams to sink in the BBR bath fluid.

The total mortar specimens did not fail in the ITT tests but exhibited deformation under loading until the limit of the equipment was reached.

No difficulty was encountered in the resilient modulus testing of the total mortar samples.

The authors indicate that the data showed close relationship between properties of total and fine mortars, and that the properties of one type of mortar can be determined from the properties of the other type.

The authors conclude the report by recommending the following:

1. Work should be continued on the fine mortar fraction since its properties are closely related to the total mortar, and since it is easier to prepare and test.
2. The asphalt cements are recommended to be aged according to the Superpave protocol before the addition of other mortar components.
3. Research is needed to develop a valid specification for the mortars.

91. Reinke, G., and Jensen, G.
Design and Construction of SMA Pavements in Wisconsin, 1996.

This paper summarizes the authors' experience with SMA mix design and construction since 1991. In the first part the author presents plots of mix characteristics versus void and low and high temperature stiffness properties, obtained from a laboratory study carried in 1993. Relative importance of percent passing the 2.36 mm (No. 8) and 4.75 mm (No. 4) sieves, asphalt content, and type of polymers are discussed.

The rest of the paper presents construction and material description about a research project devised by the Wisconsin DOT in 1992 to study several factors associated with SMA performance.

Test sections were built in three different parts of the state with different geology. Each test project consisted of six test sections of approximately 1000 feet in length. The additives used in the projects included 0.3 percent organic fiber, 0.5 percent inorganic fiber, 4 and 7 percent of Vestoplast, and 3 and 6 percent of a polymer elastomer (SBS). The mixtures were either 19.0 (3/4 inch) or 12.5 (½ inch) mm blends.

The authors present charts showing SMA gradation specifications implemented as a result of the study. It is observed that the most notable variation from the German recommendation is that a L. A abrasion value of 35 percent is specified in Wisconsin as opposed to 20 percent in Germany. Fine aggregate properties presented in the paper show that when tested in laser diffraction method, only one of the two of the fillers meet the requirement, but when tested on the basis of surface area percent the two fillers appear to be similar. Since one of the fillers was known to have been used in several projects, on the basis of the similarity in surface area the authors conclude that the other filler would perform as well.

The mix design requirements established as a result of this study are shown in the paper. Any mix additive with a favorable performance history is acceptable, and the target density is to be a minimum of 94 percent of the theoretical maximum density. The authors mention that meeting the target density has been a most difficult task.

The authors present rut depth and crack measurement data obtained from some standard, SHRP and SMA sections. The oldest of the sections was 3 years old. The rut depths between SHRP and SMA mixes compared to conventional mixes is found to be within 0.25 mm (0.01 inch). The reflective cracking for the standard, SMA and SHRP sections were 60, 42, and 29 percent, respectively. About 50 percent of the SMA sections and 100 percent of the SHRP sections had polymer additive in the mixtures. The authors mention that to fully understand the impact of different additives, cracking properties of SMA sections should be examined as a function of the additives used.

The rest of the paper discusses the methods used to design aggregate blends which would produce 3 to 4 percent air voids with 6 percent asphalt content. The authors mentions a software developed by Mathy Construction to find a blend within the permitted aggregate gradation band lines that would maximize the distance of the blend from the maximum density line.

The authors conclude by recommending research study of rubber modified asphalt cement and observing that SMA can be successfully used as rut resistant and skid resistant mixture.

92. Watson, D., and Jared, D.
Summary of Georgia's Experience with Stone Matrix Asphalt Mixes, 1996.

In this paper the authors describe the experience of Georgia DOT with Stone Matrix Asphalt (SMA) based on two research projects. Research project No. 9102 was carried out to evaluate the effect of heavy truck loading on structural and wearing courses of SMA and to compare the performance of SMA to the performance of conventional Georgia DOT mixes, and research project No. 9202 was carried out to assess the performance of SMA as an overlay for Portland cement concrete (PCC) pavement.

RESEARCH PROJECT NO. 9102

Research project No. 9102 consisted of different combinations of SMA and standard mixes on a 4 km (2-1/2 mile), high traffic volume test section on I-85. The test section had an Equivalent Single Axle Load (ESAL) of about 2 million per year.

AGGREGATE

A commonly used granite gneiss with an abrasion value of 35 % and a gneiss-amphibolite, with an abrasion value of 20 % and properties similar to the aggregates typically used in Europe, were used as aggregates for the wearing course. Coarse and fine mixes were designed for intermediate and wearing courses, respectively.

ASPHALT CEMENT

An AC-30 asphalt cement was used for the mixtures.

STABILIZER

The SMA mixture was stabilized with a low-density polyethylene thermoplastic modifier and mineral filler, mineral fiber, and hydrated lime. The modified binder had a viscosity of about 9700 poise.

MIX DESIGN AND PRODUCTION

To simulate European methods of design and construction, the mixes were designed with a 50-blow Marshall hammer and produced in a batch plant. The three modifications made to the existing plant consisted of a hopper by the side of the plant for introduction of mineral filler, an opening cut into the rear of the hopper for adding mineral fiber, and a trailer-mounted blending unit for the binder, which added the modifier to the asphalt cement. Mineral filler was blown into the extra hopper and mineral fiber was added manually through the cut in the hopper.

The mix temperature was increased to 163ºC (325ºF) to obtain greater workability with the modified binder and the mix with mineral fibers. According to the author a dry mixing time of 14 seconds and a wet mixing time of 35 seconds were required to ensure uniform distribution of the fiber and adequate coating of the aggregates.

CONSTRUCTION

A 50 mm (2.0 inch) thick SMA wearing course was placed after milling the existing pavement, over a 1.6 km (1 mile stretch) of the test section. The other 1.6 km (1 mile) part of the test section was overlaid with a 50 mm (2.0 inch) thick conventional dense graded mix after milling. Both the SMA and the conventional dense graded HMA were overlaid with 3.8 cm (1.5 inch) thick conventional fine graded mix on a 0.8 km (0.5 mile) section, and a 3.8 cm (1.5 inch) thick fine SMA course on a 0.9 km (3/4 mile) section. A 1.9 cm (0.75 inch) thick open graded friction course was placed over each of the 0.8 km (0.5 mile) conventional fine graded sections.

The SMA course was placed with a rubber tire paver equipped with a 12 m (40-foot) ski and electronic slope and grade control, and the mix was compacted with a 140 cm (56-inch) drum vibratory roller and an 7.2 - 10.8 metric ton (8-12 ton) static tandem roller with ballast.

MIX PROPERTIES AND PERFORMANCE EVALUATION

The in-place coarse SMA had an average air void content of 5.0 percent, a retained tensile strength of 99.8 percent, a loaded wheel test (8000 cycles) rutting value of 0.317 cm (0.127 inch), and a penetration value of 36 at 25ºC (77ºF). The in-place fine SMA mix had an average air void content of 6.7 percent, a retained tensile strength of 84.0 percent, a loaded wheel test (8000 cycles) rutting value of 0.142 cm (0.057 inch), and a penetration value of 35 at 25ºC (77ºF).

The in-place properties of the conventional dense graded mix are not mentioned in the paper, but the authors indicate that the in-place properties fell within the expected range.

Rut measurements were taken by Georgia DOT from both the conventional and SMA test sections in 1993, 1994, and 1995. The three year rut values were zero, 0.22 cm (0.09 inch), and 2.5 mm (0.1 inch) for the SMA mix, and 3 mm (0.12 inch), 5.25 mm (0.21 inch), and 6.75 mm (0.27 inch) for the conventional mix. According to the author, the less rutting in the SMA section confirmed the earlier measurements with the Georgia Loaded Wheel Tester, and the European experience with SMA mixes.

Frictional values were also obtained from the fine SMA in 1991, 1992 and 1996. The value increased from 42 to 50 between 1991 and 1992 and has remained the same since then. The authors comment that the thicker asphalt film of the fine SMA layer provides increased mix durability and fatigue life, and wears off quickly to provide good friction.

RESEARCH PROJECT NO. 9202

This project consisted of a 50 mm (2 inch) thick coarse SMA layer on a 0.8 km (0.5 mile) section of a high traffic volume portion of I-75. The section was placed in the outside travel lane, and had an ADT of 47,000 vehicles per day, and a truck traffic of 21 percent.

AGGREGATE

A granite gneiss/amphibolite with an abrasion value of 37 percent was used.

STABILIZER

The binder was modified with Styrene butadiene (SB). Cellulose fiber, hydrated lime, and mineral filler were also used as stabilizers.

MIX DESIGN AND PRODUCTION

The mix was designed by the 50-blow Marshall design method. A double barrel drum plant was used for production of the mix. Modifications were made to the plant to facilitate the proper addition of cellulose fiber, mineral filler, and modified binder to the mix. A maximum amount of 50 tons of mix could be stored in the silo without hampering the mix discharge.

The cellulose fibers were blown into the outer portion of the double drum at a rate of 6.8 kg per minute (15 lb per minute), at about the same time as the introduction of hydrated lime. Mineral filler was augered into the drum from a separate silo at about the same time as the baghouse dust, hydrated lime, and cellulose fibers. The binder was modified at the terminal and was transported to the construction site by tanker trucks.

CONSTRUCTION

A 50 mm (2 inch) thick coarse SMA layer was placed on a 0.8 km (0.5 mile) stretch of the milled test section. This layer was overlaid with a 38 mm (2.75 inch) thick fine SMA layer. The fine SMA layer was also placed on another 0.8 km (0.5 mile) stretch of milled conventional HMA. A 189 mm (0.75 inch) thick open graded friction course was placed on the top of the whole 1.6 km (0.8 mile) test section.

The SMA was placed with a rubber tire paver with dual inboard skis and electronic guide and slope controls, and the mix was compacted with two double drum vibratory rollers.

MIX PROPERTIES AND PERFORMANCE EVALUATION

The in-place coarse SMA mix had an average air void content of 3.6 percent, retained tensile strength of 82.7 percent, and a penetration value of 34 at 25°C (77°F). The average loaded wheel test (8000 cycles) rutting value for a composite sample of fine SMA over coarse SMA was 3 mm (0.120 inch). The in-place fine SMA had an average air void content of 5.7 percent, a retained tensile strength of 98.7 percent, a loaded wheel test (8000 cycles) rutting value of 3.15 mm (0.126 inch), and a penetration value of 31 at 25°C (77°F). The authors have not provided any in-place performance data.

The rest of the paper presents results obtained from a SMA mix optimization study, an aggregate breakdown study on research projects 9102 and 9202, an annualized cost comparison between SMA and conventional HMA, and changes made in the Georgia DOT specification on the basis of research results. The authors also provide description of two current SMA projects: a widening /resurfacing project on I-95 near Savannah and a resurfacing project for the construction of a High Occupancy Vehicle (HOV) lane in downtown Atlanta.

The mix optimization research conducted in collaboration with Georgia Tech showed that fine SMA mixes have 30 to 40 percent less rutting and 3 to 5 times greater fatigue life than a typical Georgia DOT dense graded “E” class surface mix. The Georgia Loaded Wheel Tester was used for measuring rutting susceptibility, and correlations were obtained between degree of rutting and 3:1 flatness/elongation ratio and the L.A. abrasion value of the mix. The authors present a table of maximum permitted values of L.A. abrasion and corresponding values of 3:1 flatness/elongation ratio. A maximum value of 45 is specified for both L.A. abrasion value and 3:1 flatness/elongation ratio for any combination of the two parameters. According to the authors, the study also indicated that the stringent aggregate quality control rules can be relaxed to achieve important production cost without sacrificing performance.

To observe the effect of regional variation of abrasion values of aggregates, an aggregate breakdown study was conducted with core samples obtained from fine SMA mixes used in research projects 9102 ans 9202. The I-85 project used aggregate from two different sources, and the I-75 project used aggregate from a third source. Gradation results obtained from cores taken in 1991 and 1994 for the I-85 project, and gradation results obtained from cores taken in 1992 and 1994 for the I-75 project are presented. The authors conclude that for all the mixes the amount of aggregate breakdown was small and did not vary for aggregate from different regions.

An annualized cost comparison was made between a four lane SMA and a conventional HMA overlay on an existing PCC pavement after rehabilitation by sealing and replacement of broken slabs. A 30 year life cycle period was considered, and based on European experience of 30-40 percent increase in SMA pavement life over conventional HMA, rehabilitation intervals of 10 and 7.5 years were chosen for the SMA and conventional HMA, respectively. The initial HMA overlay consisted of a 625 mm (2.5 inch) base mix, a 50 mm (2.0 inch) class “B” mix, a 37.5 mm (1.5 inch) class “E” mix, and a 42.2 kg per square meter (75 lb per square yard) open graded friction course (OGFC). The initial SMA overlay consisted of a 50 mm (2.0 inch) coarse SMA mix, a 37.5 mm (1.5 inch) fine SMA mix, and a 42.2 kg per square meter (75 lb per square yard) OGFC layer. The planned rehabilitation overlays for the HMA consisted of a 50 mm (2.0 inch) class “B” mix, a 37.5

mm (1.5 inch) class “E” mix, and a 42.2 kg per square meter (75 lb per square yard) OGFC layer. For the SMA section, the proposed rehabilitation work consisted of a 37.5 mm (1.5 inch) fine SMA mix and a 42.2 kg per square meter (75 lb per square yard) OGFC layer. The annualized costs for HMA and SMA sections were reported as $79,532 and $50,095, respectively.

Based on research results and experience with SMA since 1991, the Georgia DOT has made several changes in SMA specifications. The authors provide the revised specifications in the appendix. The important changes were the specification of a longer fiber length, development of a specification governing both SMA and OGFC mixes, increase in mineral filler tolerances, and decrease in allowable percentage passing the 4.75 mm (No. 4) sieve from 28-50 percent to 25-32 percent.

Two current SMA projects in the state of Georgia are described briefly in the paper. The widening/resurfacing project on I-95 near Savannah extends for 44 km (27.5 miles) and consist of nearly 175,500 metric tone (195,000 ton) of mix. The High Occupancy Vehicle (HOV) lane project in down town Atlanta covers nearly 48 km (30 miles) on I-85 and I-75 and consist of about 180,000 metric ton (200,000 ton) of SMA mix.

The authors make the following conclusions about benefits of SMA as realized by the combined experience of Georgia DOT and European agencies.

1. SMA has 30-40 percent less rutting than standard mixes
2. SMA has 3 to 5 times greater fatigue life
3. SMA has 30 to 40 percent longer service life (in Europe)
4. SMA has lower annualized cost of construction and maintenance

The authors indicate that the Georgia DOT plans to expand the use of SMA as surface mixes on interstate pavements.

93. Shoenberger, James E.
Construction of SMA Section at Edwards AFB, 1996.

This paper details a demonstration project in which SMA was used in lieu of a dense-graded HMA for an overlay at Edwards Air Force Base. The SMA mixture for this project was comprised of crushed stone, natural sand, fly ash, cellulose fiber, and an AR-4000 asphalt cement. [The project was constructed in 1993, therefore Superpave performance grading techniques had not been adopted.]

Shoenberger states that during the following summer, excessive amounts of bleeding had occurred in all wheel paths. He summarized several factors that contributed to the bleeding as:

1. The SMA mixture was designed with too many fines, especially passing the 4.75 mm sieve. He concluded this based on guidelines for SMA published by the National Asphalt Paving Association [Ref. 81].
2. The air void content of the compacted mixture was too low. [Air void contents presented were around 1.0 percent.]
3. Core samples obtained from the completed mat had a finer grading and higher asphalt content than specified.

The author did state that no measurable rutting had taken place in the wheel paths.

94. Scherocman, James A.
The Construction and Performance of Stone Matrix Asphalt Pavements in the United States, 1997

In this paper, Scherocman presents observations based on his experiences with the design, production, placement and compaction, and performance of SMA mixtures.

MIXTURE DESIGN

Scherocman suggests that mixture designs with SMAs containing organic fibers will yield higher optimum asphalt contents than SMA mixtures containing a polymer additive. Also, SMA mixtures containing inorganic [mineral] fibers will yield optimum asphalt contents between organic fibers and polymer additives.

Based on his experience, the Marshall stability value for specification should be 5.3 kN.

SMA mixtures with high Marshall flow values (18 to 24 (0.25mm)) are indicative of mixtures that will shove longitudinally on the roadway under compaction equipment.

Scherocman suggests that the optimum asphalt content of SMA mixtures should be selected based on 3.5 percent air voids. There should not be a minimum asphalt content specification.

MIXTURE PRODUCTION

The author notes that a significant problem encountered on several SMA projects has been the introduction of mineral filler into the asphalt plant. He suggests that mineral filler should not be introduced into the mixture production process through the cold feed aggregate conveyor belt as this can clog up dust collection systems. For batch plants, the mineral filler should be introduced into the weigh hopper and on drum mix plants it should be introduced in a manner that mixes the asphalt cement and mineral filler. These two methods ensure the mineral filler is not lost to the dust collection system.

MIXTURE PLACEMENT AND COMPACTION

Scherocman suggests two typical causes of draindown: asphalt contents that are too high and elevated mixture temperatures at the plant.

The rolldown of SMA is less than half that of conventional dense-graded mixtures.

Compaction rollers should be kept directly behind the paver. Scherocman further suggests that for best results, two breakdown rollers should be used beside each other directly behind the paver.

Pneumatic rollers should not be used for SMA compaction.

Vibratory rollers should be used to supply the initial density of SMA mixtures. The vibratory rollers should be operated in a high frequency, low amplitude mode.

PERFORMANCE

The performance of SMA pavements placed in the United States to date have been very good.

95. Brown, E. Ray and Haddock, John E.
Characterization of Stone Matrix, Asphalt Mortars, 1997

In this paper, the authors summarized the results obtained from a laboratory characterization of SMA mortars. The objectives of this study were:

1. To determine if SMA mortars could be tested using the Superpave binder equipment and test procedures;

2. If the equipment and tests could be used, to determine if they are able to identify important SMA mortar characteristics and the contribution of the different mortar constituents to the characteristics; and
3. To use the research results to set mortar specifications.

TEST PLAN

The test plan for this study was divided into two main phases: preliminary testing and fine mortar testing. The preliminary testing was published in Reference 90. Results of the preliminary testing yielded two important conclusions: the DSR and BBR could be used to test fine mortars and test results on fine mortars are closely related to test results on total mortars.

The fine mortar test plan included characterizing SMA mortars at high (58 and 70°C), intermediate (19 and 31°C), and low (-18 and -6°C) temperatures using both the DSR (high and intermediate temperatures) and the BBR (low temperatures). The tested fine mortars were prepared by varying the type of filler, percentage of filler, and type of stabilizing additive.

MATERIALS

Mineral Fillers

Filler Type	Apparent Specific Gravity	Void Volume (%)	Surface Area (m^2/g)	Percent Passing 0.075-mm Sieve	Percent Passing 0.020-mm Sieve
Limestone	2.883	33.5	1.50	79.3	57.1
Marble	2.760	40.1	0.52	61.4	28.1
Traprock	2.911	44.1	3.36	52.4	21.9
SE Fly ash	2.303	35.1	1.15	77.7	49.8
GA Fly ash	2.282	46.0	1.81	65.9	34.7
Aglime	2.702	35.8	1.31	60.2	24.1
Diabase	2.864	46.0	5.55	53.5	8.6
Wimpey	2.807	43.0	1.00	68.6	17.9
Dankalk	2.717	51.7	6.23	81.8	63.9
Oyta	2.692	65.4	4.32	74.3	56.1
Faxekalk	2.772	38.5	1.34	83.5	56.5

Asphalt Cements

Asphalt Binder Designation	Modifier	Percent Modifier by Binder Mass	PG Grade
AC-20	None	0	64-22
AC-20 M1	SBS	4	70-28
AC-20 M2	Polyolefin	8	70-22

Fibers

Property	Cellulose	Rock Wool
Bulk Density (kg/m^3)	28	--
Avg. Fiber Length (mm)	1.1	6.4
Avg. Fiber Thickness	0.045	0.005
Surface Area (m^2/g)	1.14	0.23

TEST RESULTS

To determine if the Superpave binder equipment and tests could identify important SMA mortar characteristics and the contribution of the different mortar constituents to the characteristics the authors evaluated the following properties at high, intermediate, and low temperatures.

1. Effect of filler type;
2. Effect of filler percentage;
3. Effect of stabilizer type;
4. Effect of filler particle shape;
5. Effect of filler particle size; and
6. Effect of filler surface area.

The author's findings are summarized below.

Property	Significant Trend		
	High Temp.	Intermediate Temp.	Low Temp.
Filler Type	No	Yes	No
Filler Percent	Yes	Yes	Yes
Stabilizer Type	Yes	Yes	Yes
Filler Particle Shape	Yes	No	No
Filler Particle Size	No	No	No
Filler Surface Area	Yes	Yes	No

CONCLUSIONS

Based on their results, the authors concluded that both the DSR and BBR can be used in testing SMA fine mortars. The authors also concluded that multiplying the Superpave DSR and BBR specifications by a value of 5 appears to be a good starting point for establishing SMA fine mortar specifications.

96. Louw, L. Semmelink, C.J. and Verhaeghe, BMJA
Development of a Stone Mastic Asphalt Design Method for South African Conditions, 1997

In this paper, the authors described a research study performed to develop a volumetric approach for designing SMA mixes. The authors looked at different "recipe" SMA mix design procedures currently used in South Africa, the basic principles of volumetric design, a theoretical model to determine the volumetric properties of SMA mixtures, and various compaction methods.

Based on their research the authors concluded:

1. The voids within the coarse aggregate structure should not be over filled with asphalt binder. Overfilling will cause the coarse aggregate fraction to "float" in the mortar resulting in a decrease in shear strength.
2. The Rice maximum specific gravity test [AASHTO T209] does not take into consideration the intraparticle voids of the blended aggregate. The authors state these are voids within a compacted porous aggregate which cannot be filled with asphalt binder. They suggest that the intraparticle voids should be subtracted from the measured

air voids [using AASHTO T209 and AASHTOT 166] to determine if the voids within coarse aggregate skeleton are overfilled.

3. The gyratory compactor (Troxler using 100 mm molds) should be used in lieu of the Marshall hammer.

97. Brown, E.R., Mallick, Rajib B., Haddock, John E., and Bukowski, John. *Performance of Stone Matrix Asphalt (SMA) Mixtures in the United States*

This paper presented the results of an extensive evaluation of mix design and construction data from 85 SMA projects within the United States. The findings within this paper are presented as follows:

1. Approximately 85 percent of the projects has Los Angeles abrasion values equal to or greater than 30 percent loss.
2. Approximately 90 percent of the SMA mixtures had 20 to 35 percent passing the 4.75 mm sieve and 80 percent had 7 to 11 percent passing the 0.075 mm sieve.
3. Approximately 32 percent of the projects had average laboratory air voids during construction of less than 3.0 percent. [Three to four percent air voids are more desirable.]
4. Approximately 60 percent of the projects had asphalt contents greater than 6.0 percent during production.
5. Over 90 percent of the projects had rutting measurements of less than 4mm and 25 percent had no measurable rutting. (All of the projects were located in high traffic areas.)
6. Good longitudinal joints can be constructed. The authors noted that as contractors gained experience with the construction of SMA, the quality of joints should increase.
7. Thermal and reflective cracking had not been a problem at the time of the evaluations. The authors indicated that SMA mixtures appear to be more resistant to cracking than dense-graded mixtures. They suggested this was due to the relatively high asphalt contents.
8. The authors found no evidence of raveling on the SMA projects.
9. Fat spots [segregation of mortar from coarse aggregate] appeared to be the biggest performance problem.

98. Brown, E. R., Haddock, John E., Mallick, Rajib B., and Lynn, Todd A. *Development of a Mixture Design Procedure for Stone Matrix Asphalt (SMA)*, 1997

Brown, et. al., performed a comprehensive study to evaluate recommendations made in Reference 81. Based on the results of this study, the authors produced a mixture design procedure for SMA.

The authors took the suggested requirements presented in Reference 81 and evaluated certain parameters to develop their mixture design produce. Following are the parameters suggested and the criteria tested as part of this study.

Property	Criteria Established by SMA TWG	Criteria Evaluated in SMA Mix Design Study
Coarse Aggregate:		
L.A. Abrasion (AASHTO T 96)	30 Max.	X
Flat and Elongated Particles (ASTM D4791)	3:1, 20% Max	X
	5:1, 5% Max	X
Sodium Sulfate Soundness (AASHTO T104)	15% Max	
Percent Fractures Faces		
One or more	100% Min	
Two or more	90% Min	
Absorption (AASHTO T85	2% Max	
Coarse and Fine Durability Index (AASHTO T210)	40 Min	
Fine Aggregate:	100% Crushed	
Sodium Sulfate Soundness (AASHTO T210)	15% Max	
Liquid Limit (AASHTO T89)	25% Max	

Property	Criteria Established by SMA TWG	Criteria Evaluated in SMA Mix Design Study
Total Aggregate - Gradation:		
19.0 mm	100	
12.5 mm	85-95	
9.5 mm	75 Max	
4.75 mm	20-28	X
2.36 mm	16-24	
0.60 mm	12-16	
0.30 mm	12-15	
0.075 mm	8-10	X
0.02 mm	3 Max	X

Asphalt Cement	AASHTO M226	
Mineral Filler		
PI	4 Max	
Percent Passing 20μm	20%	X
Stabilizer		
Cellulose	0.3 %	
Mineral Fiber	0.4%	
Polymer	--	
Stone-on-Stone Contact	--	X
Voids in Total Mix	3-4	X
VMA	17 Min	X
Asphalt Content	6.0% Min	X
Compactive Effort	50 Blow	X
Draindown	0.3% Max	X

RESULTS

Aggregate Toughness

To evaluate aggregate toughness as measured by the Los Angeles abrasion test, eight aggregates having abrasion loss values ranging from 17 to 55 percent were evaluated. Results of their testing showed that a good correlation existed between abrasion loss and aggregate breakdown [as measured on the 4.75 - mm sieve]. They concluded that a limit on abrasion loss is justified to minimize aggregate breakdown, and suggested a maximum abrasion loss of 30 percent.

Flat and Elongated Particle Content

To evaluate the effect of flat and elongated particles on SMA, they obtained aggregates from one source but crushed using two different methods. One method produced a high percentage of flat and elongated particles while the second produced mostly cubical aggregates. These two sources were blended at different percentages to produce the same gradation. Samples of these different mixtures were compacted with 50 blows of the Marshall hammer and the aggregate breakdown measured. Based on their test results, the authors concluded that the SMA TWG criteria for 5 to 1 was too liberal. They further concluded that 2 to 1 and 3 to 1 flat and elongated criteria would better differentiate between the various aggregates.

SMA Mixture Aggregate Gradation

The authors used previously published test results (Reference 84) to conclude that within a SMA mixture, the percent passing the 4.75-mm sieve must below 30 percent to ensure stone-on-stone contact. Stone-on-stone contact can be evaluated by plotting VMA or VCA versus the percent passing the 4.75-mm sieve. The point at which VMA begins to increase defines the condition at which a stone-on-stone contact begins to develop. Below 30 percent passing, a lowering of the percent passing begins to increase the VMA. As the percent passing, the 4.75-mm sieve decreases, the VCA also decreases. However, at approximately 30 percent passing, the slope of the line changes and the authors suggest that this is the point at which stone-on-stone contact begins to develop. Based on this work, the authors report that the dry rodded test (AASHTO T19) can be used to determine a limiting VCA.

Mineral Filler

Using the results of Dynamic Shear Rheometer testing on mortars, the authors concluded that the specification limiting the percent of filler finer than 0.02 mm should not be used.

Voids in Total Mix (VTM)

The authors used the results of a field study (Reference 97) to conclude that laboratory lab air voids should be greater than 3 percent. They also state that to minimize fat spots and rutting in warmer climates, SMA laboratory air voids should be designed closer to 4 percent.

Voids in Mineral Aggregate

Using the results of a number of SMA mixture designs and limited field experience, the authors concluded that a VMA requirement of 17 percent minimum is reasonable.

Asphalt Content

Reference 81 recommended that a minimum asphalt content of 6.0 percent should be used for SMA. Brown, et. al., state that as long as the minimum VMA requirement is met, this requirement is not needed.

Compactive Effort

Again, using the results of Reference 84, the authors conclude that 50 blows of the Marshall hammer produces mixtures of approximately equal density as 100 revolutions of a Superpave gyratory compactor.

Aggregate Breakdown

The amount of aggregate breakdown produced by the 50 blow Marshall and 100 gyrations of the SGC were quantified and compared. In addition, the authors evaluated mixtures compacted to 35 and 75 blows of the Marshall hammer and 75 and 125 gyrations of the SGC. For the Marshall hammer, the authors concluded that the amount of aggregate breakdown (as measured on the 4.75- and 0.075-mm sieves) increased as the blow count increased. Results of the mixtures compacted at the varying gyration levels with the SGC showed that the breakdown increased only slightly as the gyration level increased. When comparing the 50 blow Marshall to the 100 gyrations of the SGC, Brown, et. al, concluded that the SGC produced less aggregate breakdown.

Draindown

The authors evaluated the effect of stabilizer additive on draindown. They concluded that fiber stabilizers [mineral or fiber] were more effective than polymer stabilizers at preventing draindown.

Rut Resistance

When comparing the same mixtures as were evaluated for draindown in a Danish wheel tracking device at 55 C, the authors concluded that mixtures modified with polymers show better resistance to rutting than do mixtures containing fiber stabilizers. Interestingly, one mixture that contained no stabilizers, had the highest rutting rate during testing.

99. Brown, E. Ray and Haddock, John E.
A Method to Ensure Stone-on-stone Contact in Stone Matrix, Asphalt Paving Mixtures, 1997

In this paper, Brown and Haddock present the results of a study to develop a quantitative method to ensure when coarse aggregate stone-on-stone contact exists in an SMA mixture.

The authors present a literature review which discussed previous papers dealing with the occurrence of stone-on-stone contact within a SMA mixture. The authors mention the "30-20-10 role" [Reference 2] which suggests that a SMA should have approximately 30 percent passing the 4.75-mm sieve, 20 percent passing the 2.36-mm sieve, and 10 percent passing the 0.075-mm sieve. Also included within the literature review were discussions of research performed by Haddock, et. al. [Reference 61]., and Brown and Mallick [Reference 84].

TESTING

In order to develop a method for determining when stone-on-stone contact exists in an SMA mixture, the authors used five different compaction methods to determine VCA and five different aggregate types. The five compaction methods are as follows:

- Marshall hammer
- dry-rodded method (AASHTO T19)
- Vibrating table
- Superpave Gyratory Compactor
- British vibrating hammer

The five aggregates along with physical properties of these aggregates are as follows:

	Aggregate Type				
Property	Granite	FL Limestone	Gravel	Limestone	Traprock
Bulk Specific Gravity	2.644	2.373	2.565	2.725	2.932
Apparent Specific Gravity	2.713	2.602	2.643	2.755	3.024
Absorption, %	1.0	3.7	1.2	0.4	1.0
L.A. Abrasion, % Loss	37.0	36.0	17.0	24.0	17.0
Flat & Elongated, % 3 to 1 5 to 1	 0.6 0	 0.3 0	 1.8 0	 5.9 1.0	 1.6 0
Soundness (5 Cycles), % Loss Sodium Sulfate	0.3	12	3.3	0.2	1.1
Crushed Content, % One Face Two Faces	 100 100	 100 100	 100 67	 100 100	 100 100

Each of the coarse aggregates fractions had the same gradation except as noted below:

Sieve Size (mm)	Percent Passing
19.0	100
12.5	87
9.5	40*
4.75	0

* 20 percent for Florida limestone to increase VMA.

After the VCA of each coarse aggregate fraction only was determined by the different compaction methods, mixture designs were accomplished using 50 blows of the Marshall hammer. The VCA of the optimum specimens were then used to calculate the VCA of the compacted mixtures. Results were as follows.

Voids in Coarse Aggregate, %

		GRN	FL LMS	GRA	LMS	TRP
Marshall Hammer	Avg	32.1	26.9	33.4	29.9	35.6
	SD	0.55	0.50	0.32	0.45	0.85
Superpave Gyratory Compactor	Avg	34.7	30.3	37.2	36.6	39.2
	SD	1.30	0.84	0.40	0.25	0.42
Dry-Rodded	Avg	39.2	38.9	37.4	42.5	40.8
	SD	0.12	0.90	0.17	0.30	0.10
Vibrating Table	Avg	40.0	39.8	37.8	41.6	40.8
	SD	0.21	0.80	0.15	0.06	0.21
Vibrating Hammer	Avg	47.5	44.1	45.4	47.5	48.6
	SD	0.61	0.35	0.40	0.26	0.60

SD= Standard Deviation, GRN= Granite, FL LMS= Florida Limestone, GRA= Gravel
LMS= Limestone, TRP= Traprock

Based on these results, Brown and Haddock summarized that each of the methods produced repeatable results [because of low standard deviations.] Marshall hammer and SGC methods produced the lowest VCA values, the vibrating hammer produced the highest VCA measurements, and the vibrating table and dry-rodded test yielded approximately equal VCA values between the two extremes. They also summarized that the results indicated for a given compaction method and aggregate gradation combination, each of the compaction methods produced similar VCA values.

A concern expressed by the authors was the breakdown of the coarse aggregate fractions by each of the compaction methods. Therefore they evaluated breakdown for each of the aggregate type-compaction method combinations. Based on their testing, the Marshall hammer compaction method broke down the coarse aggregates more so than the other four methods. However, the SGC broke down the aggregate similar to the aggregate breakdown exhibited in a SMA mixture compacted with 50 blows of the Marshall hammer.

CONCLUSIONS

Brown and Haddock concluded that both the SGC and dry-rodded test should be studied further. The SGC because the aggregate breakdown was similar to mixtures compacted with a Marshall hammer and the dry-rodded because of its ease of use and repeatability.

100. Schmiedlin, Robert B.
Stone Matrix Asphalt: The Wisconsin Experience, 1998

This paper presented the results of a performance evaluation study conducted as a joint venture by the FHWA, Wisconsin Department of Transportation, and Wisconsin Asphalt Pavers Association. The data used for this performance evaluation was based on six SMA pavements and one dense-graded pavement, all constructed between 1991 and 1994. Results of the evaluation are summarized as follows:

1. The SMA pavements provided better service with regards to cracking.
2. SMAs with harder aggregates [based on L.A. Abrasion values] seemed to be providing more resistance to cracking. [The paper only distinguished the different mixtures based on hardness. No reference was made to asphalt contents or any other mixture properties. The paper did say, however, that asphalt contents for the typical SMA mixtures ranged from 6.0 to 6.7 percent. Therefore, it was unclear from the paper if the asphalt content played a role in the crack resistance of the different SMA mixtures.]
3. SMAs placed over asphalt cement concrete pavements seemed to crack at a similar rate as SMAs placed over Portland cement concrete pavements.
4. The SMA test sections provided better frictional characteristics than did the dense-graded pavement.
5. For all distress types, the SMAs performed superior to the dense-graded pavement for the time period reported. [This was based on Pavement Distress Index (PDI) surveys.]
6. For the time period reported, the SMA pavements did not provide significantly better rut resistance than the dense-graded pavements. However, the author did report that both types were "good performers." Rut depth measurements were taken with a South Dakota Road Profiler.
7. Ride data (again, South Dakota Road Profiler) indicated that the SMA pavements were "slightly" rougher when compared to the dense-graded pavement.

101. Hsu, Tung-Wen and Leu, Jeng-Thoa
Evaluation of Permanent Deformation of Stone Matrix Asphalt Mixtures, 1998

This paper describes research performed to evaluate the permanent deformation of SMA mixtures using the results of repeated load triaxial tests.

MATERIALS

Hsu and Leu used aggregates obtained from the Wu-Shi riverbed in Taiwan. These aggregates were blended into two SMA gradations (a coarse-type and fine-type) and one dense-graded gradation. The two SMA gradations were the same as have been used in Georgia [U.S.]. The dense-graded gradation was blended to meet a IVb gradation as presented in the Asphalt Institute's Manual Series No. 2 (MS-2), Mix Design Methods for Asphalt Concrete and Other Hot Mix Types, 6th Edition, 1993. The three different gradations were as follows:

Sieve Size, mm	Gradation, Percent Passing		
	IV b Dense-Graded	Coarse-Type SMA	Fine-Type SMA
25.40	100	100	100
19.05	95-100	90-100	100
12.70	75-100	45-70	85-100
9.53	65-80	25-40	60-80
4.75	45-60	22-30	25-32
2.36	30-45	18-22	18-24
1.18	21-35		
0.60	15-25		
0.30		10-20	10-20
0.150			
0.075	3-7	8-12	8-12

The asphalt binder used was an 85/100 penetration grade with the following properties:

Test Items	Asphalt Penetration Grade (85/100)
Penetration (0.1 cm)	94.0
Specific Gravity	1.026
Softening Point (C)	51.4
Flash Point (C)	310.9

MIX DESIGN

The mix design method used was a 75 blow Marshall design.

TEST SPECIMENS

Using the optimum asphalt content determined form the mix design, Hsu and Leu prepared 101.6 x 203.2-mm (4 x 8 inch) cylindrical specimens by compacting three equal lifts in a mold with 80 blows per lift applied proportionally on each lift. Specimens were prepared at optimum asphalt content and at ± 0.5 percent optimum for each gradation.

EQUIPMENT

A triaxial cell (304.8- x 406.4-mm (12 x 16 inch) which was connected with a actuated piston of a material testing machine was used. Linear variable differential transformers (LVDTs) were mounted 180 degrees on the middle section of the specimen to eliminate the effects of end restraint and possible piston friction. Within the triaxial cell, a constant deviator stress of 620.1 kPa (90 psi) and confining stress of 103.4 kPa (15 psi) was utilized. Ten thousand load repetitions were used.

RESULTS

The fine-type SMA afforded the best resistance to permanent deformation when comparing the three gradation types. For all mixture gradations, the specimens compacted with an asphalt content of 0.5 percent more than optimum exhibited more deformation.

3.0 SUMMARY

INTRODUCTION

Known by several similar names, such as Splittmastixasphalt in Europe where the material was first devised and Stone Matrix Asphalt when it was adopted in the USA, this durable, deformation-resisting mix has become generically known by its intitials SMA. Stone Matrix Asphalt is, in fact, not a particularly good translation of the German word as it fails to convey the sense of crushed stone, which is an essential feature of the mix. However, the convenient SMA form of the name will be used in this review.

SMA is a simple idea: find a hard, durable, quality stone, fracture it into roughly cubical shape and of a size consistent with the proposed layer thickness, and then glue the stones together with a durable, moisture-resistant mortar of just the right quantity to give stone-on-stone contact among the coarse aggregate particles. For the asphalt technologist, the trick is getting the various parameters right. This is where the recipes come in. Most European specifications are reflections of mix ingredients and proportions that seem to work quite well. Many specifications are based on Germany's (10) early work. The European specifications will provide the mix designer with some guidelines of what has worked when using European materials. However, specifications from other countries will not necessarily tell the designer what tests to apply or how to do a mix design. Good results are not necessarily guaranteed when different materials are used in the U.S. and when some of the European criteria are sacrificed in the name of economics or testing procedures. Still, there are remarkably few failures in SMA reported in the literature, most of the problems apparently being fatty spots in the newly laid mat (11) and one case (4) of what seems to have been a production/construction control problem has been reported.

It was not until about 1990 that interest in SMA was sparked in North America, following a study tour (26) of five European countries by a group of pavement specialists from the U.S. The favorable reaction of the team to SMA soon caught the attention of the trade press and several articles on SMA followed, especially after SMA projects were constructed first in Canada in late 1990 (24) and then in several U.S. states in 1991. Technical reports and published papers of substance relating to North American experience began to appear in late 1991.

It will be appreciated then, that the evolution of SMA in North America is a recent happening. In some respects it seems to be digressing from the European recipe-type mixes, for economic reasons and for improved HMA performance. The basic features of SMA in the U.S., i.e., gap-grading, high stone content, lots of filler, and high binder contents that are typical of European SMAs, have served as the framework for mix designs.

Another contrast between the U.S. and Europe relates to terminology, which might appear to be confusing to the casual reader. The convention in the U.S. is to speak of paving grade petroleum asphalts as asphalt cements whereas in Europe the refinery grades are referred to as bitumens. In this review, both terms are used, but an effort has been made to retain bitumen for discussions relating to SMA outside of the U.S.

DISCUSSION

In the late 1980s, the American Association of State Highway and Transportation Officials assembled a joint task force to report on rutting in asphalt pavements. The group produced a report (3), which was published in February 1989. SMA is not mentioned in the report because there was no experience among the highway agencies with SMA at the time. However, shortly thereafter, news about SMA began to circulate through exchanges of technical information between local technologists and Europeans (particularly Bellin (41), who had been loaned to the Strategic Highway Research Program (SHRP) from Lower Saxony). During the European study tour (26), U.S. pavement specialists had the opportunity to see SMA in action and hear about it through presentations such as the one by Liljedhal (8). Armed with European experience and specifications (1, 2, 4, 5, 6, 7, 9, 10, 11, 12), decision-makers in the U.S. deemed SMA worthy of trials. The first project was in Wisconsin and was reported in the trade press by Scherocman (14).

AGGREGATE QUALITY

Crushed limestone was used in the Wisconsin project although the practice in Europe generally is not to use limestone, sandstone or similar stone for coarse aggregates (20, 35, 41).

The importance of aggregate quality is acknowledged in a number of specifications. Flakiness, abrasion, polishing, and resistance to impact are only a few of the aggregate tests mentioned by various European authors (2, 11, 70). In the U.S. context, a model guideline on materials (81) addresses the issue of aggregate quality. However, stone quarry interests (71) have objected to some criteria and want to see limestone and other materials accepted for SMAs.

Gradations appear extensively throughout the papers reviewed. For comparison, many of the gradations used by authors have been repeated in the individual reviews. In the first project in the U.S., Scherocman (14) noted that the gradation followed the "30-20-10 rule", which is a useful guideline for specifiers and designers of SMA who are lacking model procedures. The rule indicates that the aggregate gradation should have 30% passing the 4.75 mm (#4) sieve, 20% passing the 2.36 mm (#8) sieve, and 10% passing the 75µm (#200) sieve.

MIX DESIGN

Other projects followed the one in Wisconsin and were also reported in the trade press before more detailed reports were published by research bodies or state highway departments (21, 22, 23, 25, 27, 28, and 29). To help potential users of SMA, Bukowski (20) produced the FHWA's work plan, which contained a summary of the first five SMAs that had been built in the U.S. in 1991. Bukowski said that these projects had generally followed the German ½-inch gradation band, which he provided in his report along with other mix design guidelines such as using 50-blow Marshall compaction and air voids between 3 and 4%. Bukowski also warned users not to be driven by Marshall stability results, noting that a failing measurement should not be the only reason for rejecting an SMA mix design. This advice is common among Europeans; the German Asphalt Pavement Association (36), Bellin (41), and Milster (53) are three examples.

One of the earliest investigations in the U.S. was conducted by Little, Dutt, and Syed, who produced an interim report (15) in 1991. However, a primary objective was to evaluate the influence of a low density polyethylene modifier (LDPE), not to evaluate the applicability of familiar tests on an unfamiliar HMA. The authors used several methods of compaction in the laboratory, including 50-blow Marshall, which is commonly used in Europe. They used several non standard tests and a Texas standard TEX-226-F for indirect tensile testing. The authors also used the Schellenberg drainage test, which Stuart (35) describes in detail. A drainage test is deemed necessary to determine the potential for the binder-rich mortar in an SMA to drain out by gravity during storage or in transit to the paving site. One of the conclusions by Little et al was that a suitably stiff mastic would probably require polymer modification. In a dramatic photograph, Milster (53) shows impressive mortar stiffness with cellulose fibers, which might indicate that polymer modification is not always necessary.

Several reports in the U.S. in 1991 and 1992 dealt with the U.S. SMA projects. Little (16), Brown (40), and Stuart (35) all performed comparative mix designs for Georgia DOT, which also produced a report (31) and supplemental specifications (32). Missouri's experience was reported by McDaniel (34). Scherocman (46, 50) and Brown (40, 48) reported on others, quite apart from numerous items in the trade press. Brown, et. al., (97) reported an evaluation of over 85 SMA projects. The practical problem of producing an SMA with cellulose fibers in a drum mixer without losing fibers in the exhaust gas dust collection system was addressed by Karnemaat, Vreibel, and Van Deusen (54) early in 1993 but this was based on experience with the earlier Michigan projects. Up to this point, it appeared that SMA mix design in the U.S. had generally followed the European guidelines although there were some variations. However, even in 1991 researchers were looking beyond the "30-20-10 rule" and European-derived guidelines. The design principle for the mortar in the Indiana SMA in October 1991 was reported by Haddock, Liljedhal, and Kriech early in 1993 (61). Briefly, their approach was based on calculating the voids in the coarse aggregate skeleton and then varying the mortar content until the correct air voids range is satisfied. Designing the mastic mortar has stretched the imagination of several authors (8, 44, 61, 64, 65, 77, 84). Recently, Carpenter (77), Brown and Mallick (84), and Brown and Haddock (99) have addressed mixture volumetrics and achievement of the stone-on-stone contact that SMA is supposed to provide in service. Brown and Mallick (84) and Brown, et. al., (98) suggest a design procedure that is intended to answer this problem. In Belgium, Francken and Vanelstraete (65) have developed a computer-aided design program.

FILLER

A fundamental question in the design of the mortar is the role of the filler. Filler means different things to different authors. In the German specification, it appears to be the material finer than 90µm (10, 36, 42, 53). McDaniel (34) in 1992, reporting on Missouri's entry into SMA in 1991, recommended a gradation for mineral filler with 70 to 100% passing the 75µm sieve and not more than 5% passing the 20µm sieve. Shelton's report (80) on Missouri's experimental SMA overlay appears to allow the regular mineral filler given in the Missouri Standard Specifications for Highway Construction except that portland cement is banned. This standard allows for 70 to 100% passing the 75µm sieve and does not say anything about smaller particle size distribution. In contrast to Missouri, a proposed specification in the United Kingdom by Walsh (70) allows portland cement.

In the literature reviewed prior to 1997, no studies were done on mortars with more than 5% passing the 20µm sieve. Scherocman and Schütz (49) expressed concern over the fineness of the filler used in Wisconsin in 1991 (39% of the filler was less than 20µm in size), although it does not seem to have adversely affected early performance (62).

Brown, et. al, (95) performed a study in 1997 stating that the amount of filler finer than 20µm was not correlated to mortar properties. They based this conclusion on mortar characterizations using the Superpave binder equipment and procedures.

According to Bellin (41), type of filler is not named in specifications or requests for proposals in Germany. He indicates that ground limestone is used and that baghouse fines are not used much. Scherocman (46) notes that baghouse fines are not normally returned into the SMA production line in Europe. There are no clear reasons for not using baghouse fines. It may be that German producers, being responsible for the mix design, and accountable for the mix, merely wish to eliminate a potential variable.

DRAINDOWN AND STABILIZING ADDITIVES

One of the questions facing mix designers is how to deal with the design of the mortar. Milster (53), in a telling photograph, illustrates the difference in stiffening effects between the mortar fractions of an SMA and a dense-graded mix. SMAs have higher asphalt cement contents than regular dense-graded mixes, which renders them vulnerable to draindown of the binder during storage or while the material is being hauled to the paving site. Bellin (41) reported that the Schellenberg draindown test is used in Germany to ensure that the mix does not lose its cementing mortar. Details of the test are reported by Stuart (35). In the United Kingdom, Walsh (70) references another test, while Brown and Mallick (84) proposed a test method, which has been accepted in the FHWA's Model Material and Construction Guidelines (81).

Stabilizing additives are used to prevent draindown. Many years ago, asbestos fibers were used but were discontinued because of health fears. In Sweden, this brought about a rapid reduction in the use of SMA (2) until the early 1980s when cellulose fibers became popular. Mineral fibers and polymers are also used to prevent draindown to improve the binder. Marek and Dukatz (71) claim that acceptable SMA mixtures can be made without fibers and that asphalt draindown can be minimized by using fines from the crushing of aggregate.

Brown, et. al., (98) looked at the effect of different stabilizing additives on draindown. They concluded that fibers (mineral or organic) did a better job of preventing draindown than did polymers.

Harders (67) used the Ring and Ball softening point test in evaluating the effect of stabilizers. Richter (19) also used this test among others that are less familiar. Serfass and Samanos (33), and Schröder and Kluge (51) have also used the softening point test. According to Schröder and Kluge, mortar compositions with softening points between 85 and 100°C provide the right viscosity and impact strength. Sometimes fibers and polymers are combined, as noted by Reinke (59) and Fujita (86); and a miltigrade asphalt has also been used as reported in theb trade press (56) and by Kriech and Haddock et. al., (57, 61).

CRUMB RUBBER

Asphalt rubber HMAs based on the SMA concept were investigated by Svec and Veizer (79) and reported in 1994. They used the German aggregate gradation. They found the 20% crumb rubber sample performed best in fatigue but the 5 or 10% crumbrubber samples performed best in indirect tension and uniaxial compression.

RUTTING RESISTANCE PERFORMANCE

A review of the literature indicates that there ate no clearly defined approaches to SMA mix design, nor are there performance-related mix tests that designers and practitioners can embrace with confidence. Despite these apparent drawbacks, SMAs in the U.S. appear to be living up to their reputation as a rut-resisting mix. In Georgia, a fine SMA without fibers performed very well in a loaded wheel rutting test as did a conventional mix. (60). Brown and Manglorkar (69) found static creep values for SMA and dense-graded mixes were about the same, but under dynamic creep testing, SMAs had slightly higher permanent strain values. Stuart and Malquist (76) used various rutting tests and concluded that stabilizing additives had no significant effect on rutting susceptibility even though optimum binder contents varied over a wide range. Mogawer and Stuart (78) used the French rut tester, the differences among the mixes tested. However, they did find that both Marshall and Gyratory compaction fractured the aggregate and altered the gradation of the mixture. Walsh (70) proposes to use a wheel tracking test at 45°C. Fujita (86) indicates that in a dynamic wheel tracking test used in Japan, SMA if far superior to regular dense-graded HMA. Hse and Leu (101) reported that axial strain measurements for SMA were less than a dense-graded mixture when tested in a triaxial cell.

OTHER USES OF SMA

Rinckes (6) and Polcak (75) deal with some less obvious applications of SMA. The former discusses the use of SMA in the Netherlands for military purposes, container terminal roads, and thin surfacings for factory floors; Polcak reports on apparent acoustical benefits derived from the use of SMA. Hoppe (18) mentions the use of SMA to achieve noise reduction near residences and its application on bridge decks. Fujita (86) also reports bridge deck applications and a thin SMA using 5 mm maximum size aggregate for resurfacing a pavement in a tunnel in Japan. Very thin surfacings of SMA have been used in France (33). In contrast to thin surfacing applications, Ohlsson and Sandin (7) report that they are considering 22 mm maximum size stone in SMA.

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