Evaluation of Stone Matrix Asphalt Versus Dense-Graded Mixtures

WALAA S. MOGAWER AND KEVIN D. STUART

Since 1991, several states in the United States have built stone matrix asphalt (SMA) pavements in order to evaluate the performance of SMA mixtures in terms of their durability and resistance to rutting. Two such SMA mixtures and two dense-graded mixtures are compared in terms of their resistance to rutting, moisture damage, low-temperature cracking, and aging, and the effect of using a polymer instead of a fiber in SMA mixtures is examined. SMA performance are evaluated using existing tests, to determine which are applicable to SMAs. U.S. Army Corps of Engineers Gyratory Testing Machine (GTM), confined and unconfined repeated load tests, diametral resilient modulus tests, the indirect tensile strength tests, and two wheel-tracking devices, the French Pavement Rutting Tester and the Georgia Loaded Wheel Tester are applied and their results analyzed. Both wheel-tracking devices and the GTM indicate that none of the mixtures is susceptible to rutting. The confined and the unconfined repeated load and diametral resilient modulus tests, however, predict more rutting in the SMAs than in the dense-graded mixtures, which contradicts the results from the wheel-tracking devices and the GTM. The SMAs had less potential for moisture damage and age hardening. When using a polymer instead of a fiber as the stabilizer in the SMAs, the amount of drained binder and mineral filler increased.

Stone matrix asphalt (SMA) was developed in Europe approximately 20 years ago. Field experience in Europe has shown SMAs to be durable and more resistant to rutting than dense-graded mixtures. Recently, the SMA technology has been implemented in the United States. Several states built SMA pavements in 1991, 1992, and 1993 to evaluate the performances of these mixtures in terms of their durability and resistance to rutting.

In principle, an SMA is to have a higher percentage of coarse aggregate in its mixture compared with that of a dense-graded mixture with a given maximum aggregate size (*1*). An SMA mixture thus provides greater stone-on-stone contact, which gives it a high resistance to rutting and should reduce the dependency of the distress on the type and amount of binder. An SMA includes a large proportion of high-quality coarse, crushed aggregate (stone); a large proportion of binder and mineral filler, including minus No. 0.075 mm dust (mastic); a small proportion of middle-sized aggregate; and, generally, a stabilizing additive to prevent drainage of the binder and mineral filler before the mixture is placed and can cool. Cellulose fibers, mineral fibers, and polymers have been used as stabilizers (*1*).

SMAs have higher binder contents than dense-graded mixtures do. An SMA's higher binder content should produce a durable mixture that is resistant to cracking, moisture damage, and age-hardening.

Several tests, available to measure the durability and rutting resistance of dense-graded mixtures, were examined to determine whether they could be used to evaluate the performances of SMAs. The objectives of the study were to

- Compare SMAs to dense-graded mixtures in terms of their resistance to rutting, moisture damage, low-temperature cracking, and aging.
- Determine which mechanical tests can be used to measure the rutting susceptibility of SMAs.

EXPERIMENTAL PROGRAM

To achieve the study's objectives, a dense gradation and an SMA gradation with a nominal maximum size of 9.5 mm (3/8 in.) and a dense gradation and an SMA gradation with a nominal maximum size of 12.5 mm (1/2 in.) were used. These mixtures were designated as D 9.5, SMA 9.5, D 12.5, and SMA 12.5. The asphalt and aggregate were the same materials used in constructing pavement sections tested by the Accelerated Loading Facility (ALF) at the Turner-Fairbank Highway Research Center (TFHRC). The asphalt was an AC-20, and the aggregate was a crushed diabase. The aggregate gradation of each mixture is presented in Table 1 and illustrated in Figure 1. For the SMAs, the aggregates were blended according to gradations presented in an FHWA report on SMAs that were developed based on German specifications (*1*). The SMA 12.5 also met the target gradation ranges recommended by the FHWA plan for the test and evaluation of SMA (*2*). The D 9.5 gradation was prepared to meet the Virginia Department of Transportation S-5 specifications for surface mixtures.

The four mixtures were evaluated in terms of their resistance to rutting, moisture damage, low-temperature cracking, and aging. The two SMAs were prepared using Arbocel 50/50 (i.e., pellet composed of 50 percent cellulose fiber and 50 percent asphalt) as the stabilizer, at 0.6 percent by total weight of the mixture.

A polymer stabilizer called Vestoplast was also used at 7 percent by weight of the asphalt in order to investigate the effect of using a polymer instead of a fiber. The SMAs with Vestoplast were compared with the other mixtures in terms of their resistance to rutting and drainage potential only. The SMAs with Vestoplast resistances to rutting were evaluated using two-wheel-tracking devices only.

Mix Design

Marshall mix designs were performed to determine the optimum asphalt contents (OAC). The mixtures were designed to sustain heavy traffic. The SMAs were compacted using 50 blows, whereas the dense-graded mixtures were compacted using 75 blows.

SMAs are designed in Europe for heavy traffic using 50 blows. Increasing the number of blows is not recommended because it

---

W. S. Mogawer, Civil Engineering Department, University of Massachusetts Dartmouth, North Dartmouth, Mass. 02747. K. D. Stuart, FHWA, Turner-Fairbank Highway Research Center, 6300 Georgetown Pike, McLean, Va. 22101-2627.

TABLE 1 Aggregate Gradations of Mixtures Tested (Percent Passing)

Sieve Size mm	in	D 9.5 (1)	SMA 9.5 (2)	SMA 9.5 (3)	SMA 9.5 (4)	D 12.5 (1)	SMA 12.5 (2)	SMA 12.5 (3)	SMA 12.5 (4)
19.0	(3/4 in)					100.0	100.0	100.0	100.0
12.5	(1/2 in)	100.0	100.0	100.0	100.0	95.0	95.0	95.5	94.6
9.5	(3/8 in)	95.0	95.0	95.1	94.5	82.0	71.0	74.5	76.1
4.75	(No. 4)	66.0	46.0	50.8	52.9	56.0	25.0	33.4	34.4
2.36	(No. 8)	48.7	25.0	29.6	31.0	39.0	20.0	24.1	24.2
1.18	(No. 16)	37.2	20.0	23.4	23.4	29.0	18.0	20.7	20.5
0.600	(No. 30)	26.9	16.0	19.0	18.8	21.0	16.0	18.1	17.9
0.300	(No. 50)	16.0	13.0	15.6	15.4	13.8	13.0	15.2	14.9
0.150	(No. 100)	8.7	12.0	13.7	13.6	9.1	12.0	13.3	13.3
0.075	(No. 200)	6.7	10.0	11.4	11.2	6.3	10.0	10.9	11.1

(1) and (2): Design Gradations.
(3): Extraction results of samples prepared using the GTM.
(4): Extraction results of samples prepared using the Marshall hammer.

could increase the number of fractured aggregates without increasing density (*1*).

The design air-void contents were 4 percent for the dense-graded mixtures and 3 percent for the SMA's. These are typical average design contents. The greater stone-on-stone contact in an SMA allows the use of lower air voids.

Rutting Evaluation

The French Laboratoire des Ponts et Chaussées (LCPC) Pavement Rutting Tester, the Georgia Loaded Wheel Tester (GLWT), the U.S. Army Corps of Engineers Gyratory Testing Machine (GTM), and a confined and unconfined repeated load test were used to measure the resistance to rutting.

French Pavement Rutting Tester

The French Pavement Rutting Tester tests slabs that are 500 by 180 by 50 mm thick (19.7 by 7.1 by 1.97 in.) using a smooth, reciprocating, pneumatic rubber tire at 0.61 MPa (87 lbf/in.^{2}) and loaded at 5000 ± 50 N (1124 lbf). The tire is 415 mm (16.3 in.) in diameter and 109 mm (4.3 in.) wide. A hydraulic jack underneath the slab pushes the slab upward to create the load. The machine has two reciprocating tire assemblies and tests two slabs at a time. The slabs were fabricated using the French Plate Compactor and were cured at room temperature for 2 days.

An initial densification of 1,000 cycles at 25°C (77°F) is first applied. A cycle is two passes of the tire. The deformations in the slabs are measured at the end of the initial densification. These readings are the zero readings. The slabs are then heated to the test tempera-

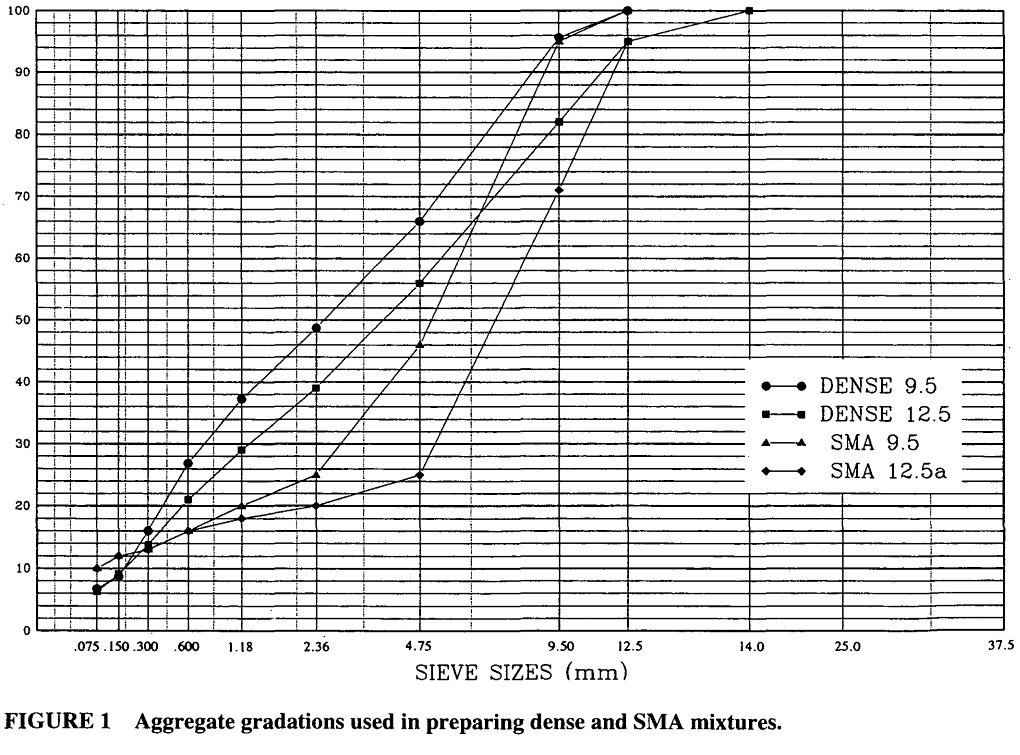

FIGURE 1 Aggregate gradations used in preparing dense and SMA mixtures.

ture of 60°C (140°F) for 3 hr before the test begins. The average rut depths at 30, 100, 300, 1,000, and 3,000 cycles are measured. To measure the rut depth, the machine is stopped and 15 measurements on the slab are taken to calculate the average rut depth: 5 locations along the length times three locations along the width. The test is stopped if the average rut depth is more than 20 percent of the slab thickness (*3*). Three slabs were fabricated at the OAC for each mixture.

Before testing, each slab's air voids were calculated using the slab density and the maximum specific gravity of the mixture. After testing, each slab was cut into three pieces along the length of the slab, two pieces out of the wheel path, and one piece in the wheel path. The air voids in each piece were measured. The voids before testing and the voids out of the wheel path after testing were expected to be close; however, the voids out of the wheel path were higher. This means that the voids in the wheel path must be measured before testing using trial slabs.

Georgia Loaded Wheel Tester

GLWT tests a 381-mm by 76.2-mm by 76.2-mm (15-in. by 3-in. by 3-in.) beam for rutting at 40.6°C (105°F). The beams are prepared by compression. Densities within 97 percent of the mix design density are recommended (*4*).

To achieve the recommended density, a 444.8-kN (100-kip) load was applied rapidly four times and then applied for 6 min. A load of 266.9 kN (60 kip) was used instead for the Vestoplast mixtures because binder squeezed out of the beams using 444.8 kN (100 kip). Nevertheless, the required air-void level of 3 percent was still met.

Before testing, beams were cured at room temperature for 7 days, then cured for 24 hr at 40.6°C (105°F). After curing, each beam was loaded into the testing frame of the GLWT; an initial reading was taken at the beam's center, at 50.8 mm (2 in.) left of the center, and at 50.8 mm (2 in.) right of the center, across the length of the beam. A 0.69-MPa (100-lbf/in.^{2}) inflated rubber hose was positioned across the sample and a loaded wheel ran back and forth on the top of the rubber hose. When the wheel moved from right to left, the load was approximately 740 N (166.3 lbf) at the center of the beam, whereas it was 630 N (141.6 lbf) when moving left to right.

The test was performed for 8,000 cycles, and final readings were taken at the same positions at which initial readings were taken. If the average rut depth for the three beams exceeded 7.6 mm (0.30 in.), the mixture was considered to have failed (*4*). Three beams were fabricated at the OAC for each mixture.

GTM

The GTM was used to evaluate rutting resistance, using the gyratory stability index (GSI) and the refusal densities.

The refusal density is where there is no reduction in air voids with additional gyrations. The GSI is the ratio of the maximum gyratory angle to the minimum gyratory angle that occurs during the test. Typically, for stable mixtures, the GSI value is close to 1.0; for unstable mixtures, the GSI is significantly above 1.1 (*5*). A more definitive failing GSI has not been established.

The mixtures were tested at 60°C (140°F) in accordance with the National Cooperative Highway Research Program (NCHRP) Asphalt-Aggregate Mixture Analysis System (AAMAS) procedure (*6*). Three specimens were fabricated at the OAC for each mixture. All specimens were tested with a vertical pressure of 0.83 MPa (120 lbf/in.^{2}) and a 0.0175-rad (1°) gyratory angle. The GTM oil-filled roller was used. Samples were compacted to 300 revolutions. Extraction tests and sieve analyses were performed on the SMA specimens to determine whether the GTM fractured any aggregate.

Compressive Repeated Load Test

Unconfined repeated load tests were performed under compression to determine the dynamic modulus and permanent deformation of each mixture. The specimens had a diameter of 101.6 mm (4.0 in.) and a height of 203.2 mm (8.0 in.) and were compacted to the design air-void levels using kneading compaction. Testing was performed at 40°C (104°F) using a closed-loop servohydraulic MTS Materials Testing System. Vertical compressive strains were measured by averaging the outputs of two linear variable differential transducers (LVDT), each having a gauge length of 101.6 mm (4.0 in.).

A repeated load consisting of a 0.1-sec sinusoidal wave followed by a 0.9-sec rest period was applied to each specimen. The vertical stress was 0.45 MPa (65 lbf/in.^{2}). The dynamic modulus and its associated permanent deformation at the hundredth cycle were used to evaluate the mixtures.

Also, two confined repeated load tests were performed on the SMA 12.5. One test consisted of a 0.59-MPa (85-lbf/in.^{2}) vertical stress and a 0.14-MPa (20-lbf/in.^{2}) confining pressure, which provided a deviator stress of 0.45 MPa (65 lbf/in.^{2}). The other test consisted of a 0.45-MPa (65-lbf/in.^{2}) vertical stress and a 0.14-MPa (20- lbf/in.^{2}) confining pressure, which provided a deviator stress of 0.31 MPa (45 lbf/in.^{2}).

Moisture Damage Evaluation

The resistance to moisture damage was evaluated by determining the diametral modulus (M_d) and static indirect tensile strength (S_t) of specimens before and after exposure to water (*7*). Six specimens per mixture were compacted using the Marshall hammer to air-void levels expected in the field after construction. Dense-graded mixtures were compacted to 6- to 8-percent air voids. The Swedes and Germans report that, for SMAs, field air-void levels are typically 3 to 5 percent and are specified to be less than 6 percent (*1*). Thus, the SMAs were compacted to a 5 to 6-percent air-void range. The six specimens were then divided into two sets. One set was maintained in a dry state; the other was vacuum saturated with distilled water so that 55 to 80 percent of the air voids were (*a*) filled with water, (*b*) subjected to freezing for 15 h at −18 ± 2.0°C (−0.4 ± 3.6°F), then (*c*) moisture conditioned by soaking the specimens in distilled water at 60°C (140°F) for 24 hr, and (*d*) soaked in distilled water at 25°C (77°F).

Moisture damage is presented as the ratio of the wet M_d to the dry M_d (M_dR) as well as the ratio of the wet S_t to the dry S_t (TSR). Mixtures with a TSR less than 0.8 or an M_dR less than 0.7 have a moisture-damage potential (*7*).

Visual stripping was also estimated; Above 10 percent, it was considered excessive (*7*).

Low-Temperature Cracking Evaluation

High stiffnesses, or moduli, of asphalt mixtures at cold temperatures are equated with low flexibility and an increased susceptibility to cracking. In this study, three Marshall specimens per mixture were prepared and tested for M_d at −32, −24, −16, −8, 0, 5, 16, 25, 32, and 40°C (i.e., −25.6, 11.2, 3.2, 17.6, 32, 41, 60.8, 77, 89.6, and 104°F).

Drainage

The German drainage test, the FHWA drainage test for open-graded friction courses (OGFC), and a proposed drainage test developed in the Bituminous Mixtures Laboratory at TFHRC were included in this study to determine the efficiency of the two stabilizers used to prevent drainage of the binder and mineral filler.

For the German drainage test, 1 kg (2.2 lbm) of mixture is prepared at the mixing temperature. The mixture is then placed into a dried 800-ml glass beaker and weighted to the nearest 0.1 g (0.00022 lbm). The beaker is covered and stored for 60 ± 1 min at 170°C (338°F). After storage, the mixture is removed from the beaker and placed into a tared bowl by quickly turning the beaker upside down without shaking. The final weight of the mixture is measured, and the percent drainage is calculated as

$$\text{Loss (percent)} = \frac{100\ (\text{original weight} - \text{final weight})}{\text{original weight}}$$

Losses of less than 0.2 percent indicate that drainage should not occur, although losses of up to 0.3 percent are still acceptable. Losses greater than 0.3 percent indicate that drainage may be a problem (*1*). The storage temperature used in Germany is the hot-mix discharge temperature, which is much higher than those used in the United States. Hence, the procedure was modified so that the compaction temperature of 143°C (290°F) could be used.

The FHWA's OGFC drainage test uses a clear pyrex pie plate, 203.2- to 228.6-mm (8- to 9-in.) in diameter, instead of a beaker. The amount of drainage is observed on the bottom of the plate and compared to standard pictures of drainage, ranging from no drainage to excessive drainage.

In the proposed drainage test, called the 2.36-mm (No. 8) sieve drainage test, a dried mixing bowl is weighed to the nearest 0.1 g (0.00022 lbm). A 2.36-mm (No. 8) sieve of similar diameter is placed on top of the bowl, and 1 kg (2.2 lbm) of mixture is placed on the sieve immediately after mixing. The bowl, sieve, and mixture are then covered with aluminum foil and stored for 60 ± 1 min at 143°C (290°F). After storage, the sieve is removed and the final weight of the bowl is obtained. The percent loss resulting from drainage is calculated as

$$\text{Loss (percent)} = \frac{100\ (\text{final bowl weight} - \text{initial bowl weight})}{\text{original weight of mixture}}$$

The German test criteria (i.e., losses less than 0.2 percent indicate no drainage problem) was also applied to this test.

Aging

The effect of aging on the mixtures was examined according to Strategic Highway Research Program (SHRP) Method M-007 (*8*). The procedure consists of determining the effects of short- and long-term aging on asphalt mixture stiffness. For short-term aging, loose mixtures were aged in a forced draft oven for 4 hr at 135°C(275°F) and then compacted using the Marshall hammer to an air-void level expected in the field. Dense-graded mixtures were compacted to 6- to 8-percent air voids. SMAs were compacted to 5- to 6-percent air voids. The M_d of each compacted mixtures was measured at 25°C (77°F). For long-term aging, the compacted mixtures were aged in a forced draft oven for 5 days at 85°C (185°F). Each mixture's M_d and tensile strength were then measured.

RESULTS AND ANALYSIS

Mix Design

The Marshall-mix design results are presented in Table 2. Dense-graded mixtures had higher stabilities and lower flows than the SMAs. This could be because of the higher binder contents of SMAs. The D 12.5 had lower voids in mineral aggregate (VMA) than the D 9.5, resulting in a lower binder content for the D 12.5 mixture—the typical relationship. The reverse was true for SMAs. Both SMAs 12.5 had slightly higher VMAs than the SMAs 9.5, resulting in higher binder contents for the SMAs 12.5. This is proba-

TABLE 2 Mixture Design Properties and Materials

Mixture Type	OAC (%)	Stability (N)	Flow (0.25 mm)	Air Voids (%)	VMA (%)
D 9.5	5.2	15 450	11.0	4.0	14.8
SMA 9.5 Arbocel	6.3	9 510	12.5	3.0	16.3
SMA 9.5 Vestoplast	6.5	9 483	14.5	3.0	16.8
D 12.5	4.5	17 066	10.7	4.0	13.7
SMA 12.5 Arbocel	6.7	7 116	14.3	3.0	17.5
SMA 12.5 Vestoplast	6.8	8 286	18.2	3.0	17.7

1 lbf = 224.72 kN
1 in = 25.64 mm.

bly related to the choice of the gradation. Opening up the gradation of the SMA 9.5 by reducing the percent passing the 4.75-mm (No. 4) and 2.36-mm (No. 8) sieves might provide a higher VMA. The VMAs of each SMA did not vary with binder content, and the air voids versus binder content relationships were generally linear. The only exception was for the SMA 9.5 with Vestoplast, for which the air voids versus binder content relationship was curvilinear, as air voids less than 3 percent could not be obtained. Only three binder contents were used in designing the SMA mixtures.

Rutting Evaluation

French Pavement Rutting Tester

Percent rut depths are presented in Table 3. The percent rut depth in all mixtures at the different number of passes was less than 20 percent of the specimens' thickness. Hence, all of the mixtures passed. A statistical comparison of the percent rut depths, both between the D 9.5 and two SMAs 9.5 and between the D 12.5 and two SMAs 12.5 (at a level of significance $\alpha = 0.05$ using a *t*-test) revealed no significant difference for the various numbers of passes. If 3,000 cycles represents pavement service life, then all six mixtures will not have a rutting problem in the field.

Georgia Loaded Wheel Tester (GLWT)

The rut depths and air voids are presented in Table 4. All six mixtures had rut depth less than 7.6 mm (0.30 in.). The SMAs as well as the dense-graded mixtures were not rut susceptible. Statistical comparisons of the rut depths between the D 9.5 and the SMAs 9.5 and between the D 12.5 and the SMAs 12.5 (at a level of significance $\alpha = 0.50$ using a *t*-test) revealed no significant difference between the mixtures.

Gyratory Testing Machine Results (GTM)

The results from the GTM are presented in Table 4. The GSIs of the mixtures were not significantly different and indicated that none of the mixtures should rut. This result agrees with the results from the wheel-tracking devices. Extractions were performed on the SMAs with Arbocel before and after testing. The results are presented in Table 1. The results show a significant increase in the percentage of aggregate passing the 4.75-mm (No. 4) and 2.36-mm (No. 8) sieves. Hence, the GTM fractured the aggregate. Based on this result, it was decided that the effect of the Marshall compaction process on the SMA gradations should also be examined. Therefore, the SMAs with Arbocel were compacted using the Marshall hammer and extractions were performed. The extraction results are also presented in Table 1. Marshall compaction had the same effect on gradation. Because aggregate gradation is an important factor in designing SMAs, the GTM and Marshall hammer compaction methods used in this study may be affecting the mixture design adversely.

Compressive Repeated Load Test

Moduli and permanent deformations are presented in Table 5. Because of the stone-on-stone contact that occurs in SMAs, they were expected to have lower permanent deformations than dense-graded mixtures. However, the unconfined repeated load test showed that both SMAs had significantly higher average permanent deformations than the dense-graded mixtures tested. Applying a 0.14-MPa (20-lbf/in.^{2}) confining pressure and a 0.59-MPa (85-lbf/in.^{2}) or 0.45-

TABLE 3 French Pavement Rutting Tester Results—Percent Rut Depth

Number of Cycles	D 9.5	SMA 9.5 Arbocel	SMA 9.5 Vestoplast	D 12.5	SMA 12.5 Arbocel	SMA 12.5 Vestoplast
30	0.4	0.6	4.5	0.3	2.3	4.0
100	1.3	1.8	5.7	0.9	3.2	5.3
300	1.6	2.4	7.1	1.4	3.8	5.8
1000	3.0	2.9	7.7	2.3	4.3	6.5
3000	4.0	3.3	8.5	3.4	5.3	7.3

TABLE 4 Georgia Loaded Wheel Tester and GTM Results

Mixture Type	GLWT		GTM	
	Rut (mm)	Air Voids (%)	GSI	Refusal Air Voids (%)
D 9.5	4.67	4.26	1.02	3.90
SMA 9.5 with Arbocel	4.04	2.82	1.02	2.04
SMA 9.5 with Vestoplast	4.06	2.89	NT	NT
D 12.5	3.20	3.69	1.04	3.30
SMA 12.5 with Arbocel	3.96	2.76	1.01	2.10
SMA 12.5 with Vestoplast	3.47	2.68	NT	NT

NT: Not tested.

1 in = 25.64 mm.

TABLE 5 Compressive Repeated Load Test Results

	D 9.5	SMA 9.5 Arbocel	D 12.5	SMA 12.5 Arbocel		
				Unconfined	Confined	
					(1)	(2)
Modulus (MPa)	1020	885	791	742	845	1062
Permanent deformation (x 10^{-2} mm)	5.3	14.4	6.3	17.6	14.1	10.4
% Air Voids	3.5	3.3	4.3	3.4	2.1	2.1

(1): 0.45-MPa (65-lbf/in^2) deviator stress.
(2): 0.31-MPa (45-lbf/in^2) deviator stress.

lbf/in^2 = 145.03 MPa.
1 in = 25.64 mm.

MPa (65-lbf/in.^{2}) vertical pressure did not improve the data (i.e., permanent deformations for SMA 12.5 did not drop). A test using 101.6-mm (4.0-in.) by 203.2-mm (8.0-in.) specimens might not apply to an SMA.

Moisture Damage Evaluation

Visual Stripping

Average percentages of visual stripping are presented in Table 6. Both SMAs with Arbocel had less visual stripping than the dense-graded mixtures. The D 9.5 and the D 12.5 had visually stripped areas of 30 and 25 percent, respectively. The SMA 9.5 and the SMA 12.5 had visually stripped areas of 15 and 10 percent, respectively. The lower percentage of visual stripping in the SMAs could be related to their higher binder contents, which increase the asphalt film around the aggregates.

Tensile Strength Ratio (TSR)

Tensile strengths and TSRs of the mixtures are summarized in Table 6. Statistically, there was no significant reduction in the tensile strength of either SMA from moisture conditioning. Both SMAs had a TSR close to 100 percent. Statistically, the tensile strengths of the dense-graded mixtures were significantly reduced by moisture conditioning. This reduction resulted in TSRs below 80 percent. Testing indicates that the SMAs are more resistant to moisture damage than are dense-graded mixtures.

Diametral Modulus Ratio

The dense-graded mixtures each had a diametral modulus ratio (M_dR) of less than 70 percent, whereas the SMAs tested each had an M_dR that was greater than 70 percent. Thus, testing indicates that the SMAs were less susceptible to moisture damage than were the

TABLE 6 Resistance to Moisture Damage Results

	D 9.5	SMA 9.5 Arbocel	D 12.5	SMA 12.5 Arbocel
Tensile Strength, 25 °C (77 °F)				
Average Dry, kPa	628.1	504.7	632.3	422.0
Average Wet, kPa	358.5	502.6	450.9	400.6
Retained Ratio (TSR), percent	57.1	99.6	71.3	95.0
Diametral Modulus, 25 °C (77 °F)				
Average Dry, MPa	1125.9	1165.9	1350.7	1048.0
Average Wet, MPa	456.4	913.6	692.9	748.1
Retained Ratio (M_dR), percent	40.5	78.4	51.3	71.4
Average Visual Stripping, percent	30.0	15.0	25.0	10.0
Average Swell, percent by volume	0.6	0.3	0.2	0.1
Average Air Voids, percent	7.0	5.5	6.9	5.5

lbf/in^2 = 145.03 MPa.

TABLE 7 Diametral Modulus Results (MPa) for Low-Temperature Cracking

Temperature °C (°F)	D 9.5	SMA 9.5 Arbocel	D 12.5	SMA 12.5 Arbocel
-32 (-25.6)	45 640	43 208	51 450	43 580
-24 (-11.2)	43 550	42 670	45 470	36 300
-16 (3.2)	38 850	36 230	43 420	32 710
-8 (17.6)	34 040	30 830	36 690	26 940
0 (32.0)	17 670	16 030	21 620	15 420
5 (41.0)	12 300	10 610	14 390	9 870
16 (60.8)	4 160	3 890	4 900	3 310
25 (77.0)	1 480	1 410	1 870	1 240
32 (89.6)	650	660	860	550
40 (104.0)	340	320	430	260

lbf/in^2 = 145.03 MPa.

dense-graded mixtures. A *t*-test was performed at a level of significance $\alpha = 0.05$ to compare the wet and dry M_d of each mixture. These analyses revealed that the wet M_d of the dense-graded mixtures was significantly lower than mixtures dry M_d.

A *t*-test showed there was not a significant difference between the wet M_d and the dry M_d of SMA 9.5. However, SMA 12.5 had a significantly lower wet M_d than dry M_d and it had a borderline M_dR. Therefore, for this mixture, the M_d test measured susceptibility to moisture damage better than the TSR test.

Low-Temperature Cracking Evaluation

Results of the low-temperature cracking evaluation are tabulated in Table 7. A *t*-test statistical comparison of the M_d data for the SMA 12.5 and D 12.5 (at a level of significance $\alpha = 0.05$) revealed that the stiffnesses of the SMA 12.5 were significantly lower than that of the D 12.5 mixture. This implies that the SMA will be less susceptible to low-temperature fracture but more susceptible to rutting at high temperatures. Test results at the high temperature contradict the French Pavement Rutting Tester, GLWT, and GTM results, however; they showed no significant difference in the rutting susceptibility. Hence, diametral configuration may not be a good method for determining the rutting susceptibility of SMA mixtures. There was no significant difference in M_d between the D 9.5 and the SMA 9.5.

Drainage

Drainage test results are presented in Table 8. The three drainage tests showed that the SMA 12.5 with Vestoplast had a high amount of drainage. The gradation may have to be altered to reduce the amount of drainage. The other three mixtures passed all tests, including the SMA 9.5 with Vestoplast.

Aging

Aging results are presented in Table 9. Increases in stiffness for the dense-graded mixtures related to short- and long-term aging were significantly higher than the increases for the SMAs. Also, the increases in tensile strength for the dense-graded mixtures after long-term aging were significantly higher than the increases for SMAs indicating that dense-graded mixtures might be more susceptible to cracking than the SMAs after they are age hardened.

CONCLUSIONS

Rutting Evaluation

- The SMAs with Arbocel and the dense-graded mixtures passed the French Pavement Rutting Tester, GLWT, and GTM. The SMA's with Vestoplast passed the two tests performed on them, namely, the French Pavement Rutting Tester and the GLWT. This means that none of the mixtures were susceptible to rutting.
- The unconfined, compressive, repeated load test showed more permanent deformation for SMAs than for dense-graded mixtures, and applying a confined pressure did not improve the results.
- The diametral configuration may not be a good method for determining the rutting susceptibility of SMAs at high temperatures.

TABLE 8 Drainage Test Results

Test Type	SMA 9.5		SMA 12.5	
	Arbocel	Vestoplast	Arbocel	Vestoplast
German Test, % loss	0.10	0.31	0.08	3.21
FHWA Open-Graded Friction Course Test, drainage level	Slight	Slight	Slight	Excessive
2.36-mm (No. 8) Sieve Drainage Test, % Loss	0.00	0.02	0.11	2.13

TABLE 9 Aging Test Results

	Dynamic Modulus, M_d at 25 °C, MPa			Change in M_d		
Type of Mix	Unaged	Short-Term Aging	Long-Term Aging	Short-Term to Unaged	Long-Term to Short-Term	Total Aging
D 9.5	1126	2570	3943	1444	1373	2817
SMA 9.5 Arbocel	1166	2283	3094	1177	811	1928
D 12.5	1351	2981	4625	1630	1644	3274
SMA 12.5 Arbocel	1048	1555	2133	507	578	1085

	Tensile Strength at 25 °C, kPa		Change in Tensile Strength
	Unaged	Long-Term Aging	Total Aging
D 9.5	628	1314	686
SMA 9.5 Arbocel	505	960	455
D 12.5	632	1267	635
SMA 12.5 Arbocel	422	671	249

1.8(°C) + 32 = °F
lbf/in^2 = 145.03 MPa

Moisture Damage Evaluation

- The SMAs had lower percentages of visual stripping than the dense-graded mixtures. This could be because of high binder contents in SMAs, which increase the asphalt film around the aggregates.
- The TSR and M_dR indicated that the SMAs had less potential for moisture damage than the dense-graded mixtures.

Low-Temperature Cracking Evaluation

- There was no significant difference in the resistance to low-temperature cracking between the D 9.5 and the SMA 9.5 with Arbocel.
- The SMA 12.5 with Arbocel had a significantly lower stiffness than the D 12.5. This implies that the SMA 12.5 will be less susceptible to low-temperature cracking.

Drainage

- All three drainage tests performed in this study showed that the SMA 12.5 with Vestoplast has an unacceptable level of drainage.

Aging

- The increase in stiffness and tensile strength from aging was significantly higher in dense-graded mixtures than in SMAs. This indicates that dense-graded mixtures might be more susceptible to cracking than SMAs after they age harden.

Note that both the GTM and the Marshall hammer fractured the aggregates of the SMA mixtures, as evidenced by the extraction test results.

ACKNOWLEDGMENT

This study was funded by FHWA and was performed at the FHWA Turner-Fairbank Highway Research Center in McLean, Virginia.

REFERENCES

1. Stuart, K. D. *Stone Mastic Asphalt (SMA) Mixture Design.* Report FHWA-RD-92-006. FHWA, U.S. Department of Transportation, March 1992.
2. SMA Technical Working Group. *SMA Material and Construction Model Specification.* FHWA, Office of Technology Applications. U.S. Department of Transportation, March 1, 1992.
3. Brosseaud, Y., J. L. Delorme, and R. Hiernaux. Use of LPC Wheel-Tracking Rutting Tester To Select Asphalt Pavements Resistant to Rutting. In *Transportation Research Record 1384.* TRB, National Research Council, Washington, D.C., 1993.
4. Lai, J. S. *Development of a Laboratory Rutting Resistance Testing Method for Asphalt Mixtures.* Research Project No. 8716. Final Report. Georgia Department of Transportation. Atlanta, Aug. 1989.
5. Roberts, F. L. P. S. Kandhal, E. R. Brown, D. Y. Lee, and T. W. Kennedy. *Hot Asphalt Materials, Mixtures Design, and Construction.* National Asphalt Pavement Association Education Foundation, Lanham, Md. 1991.
6. Von Quintus, H. L., J. A. Scherocman, C. S. Hughes, and T. W. Kennedy. *NCHRP Report 338: Asphalt-Aggregate Mixture Analysis System.* TRB, National Research Council, Washington, D.C., 1991.
7. Stuart, K. D. *Evaluation of Procedures Used to Predict Moisture Damage in Asphalt Mixtures.* Report FHWA-RD-86-090. FHWA, U.S. Department of Transportation, Sept. 1986.
8. "Short- and Long-Term Aging," Method M-007. Strategic Highway Research Program. National Research Council, Washington, D.C. Sept. 25, 1992.

Publication of this paper sponsored by Committee on Characteristics of Bituminous Paving Mixtures To Meet Structural Requirements.