Effect of Coarse Aggregate Content on Stone Matrix Asphalt Rutting and Draindown

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The stone matrix asphalt (SMA) technical working group (TWG), composed of federal, state, and industry representatives, was formed in 1992. The SMA TWG developed the *SMA Model Material and Construction Guidelines*. The model suggests using 20 to 28 percent passing the 4.75-mm sieve size. The effects of coarse aggregate content on the performance and draindown characteristics of SMA mixtures was evaluated. Performance was evaluated in terms of rutting using three wheel-tracking devices: the French pavement rutting tester, the Georgia loaded-wheel tester, and the German Hamburg wheel-tracking device. Draindown was evaluated using four tests: the German draindown test, the FHWA draindown test for open-graded friction courses, a proposed draindown test developed in the Bituminous Mixtures Laboratory at the Turner-Fairbank Highway Research Center, and the National Center for Asphalt Technology draindown test. Also, the effects of using a polymer instead of a fiber as the stabilizer in the SMA mixtures were examined. Data from the draindown tests and wheel-tracking devices showed that decreasing the coarse aggregate content reduced the amount of draindown without affecting the mixture performance in terms of rutting. When using a polymer instead of a fiber, the amount of mastic that drained down increased. On the basis of the Georgia loaded-wheel tester and the Hamburg wheel-tracking device, mixtures with the polymer had significantly lower rut depths than the mixtures with fiber. On the basis of the French pavement rutting tester, mixtures with the polymer had significantly lower rates of rutting (slopes) than mixtures with the fiber, but the rut depths at the end of the test were not statistically different.

Stone matrix asphalt (SMA) is a gap-graded hot mixture that maximizes the binder and coarse aggregate contents. SMA mixtures have high proportions of coarse aggregate, binder, and mineral filler, and low proportions of middle-size aggregates compared with dense-graded mixtures. Cellulose fibers, mineral fibers, and polymers have been used as stabilizing additives to prevent draindown of the mastic before the SMA is placed and is allowed to cool (*1*).

SMA was developed in Europe more than 20 years ago. SMA mixtures in Europe have been shown through field experience to be durable and more resistant to rutting than dense-graded mixtures. More than 50 SMA pavements have been built in the United States, and additional projects have been proposed.

An SMA technical working group (TWG) composed of federal, state, and industry representatives was formed in 1992. The group assists in analyzing SMA technology and coordinating the dissemination of SMA-related information. The SMA TWG developed the *SMA Model Material and Construction Guidelines* (*2*). This model includes mixture, coarse and fine aggregate, stabilizer, and binder requirements for SMA mixtures. For coarse aggregates, the model suggests using 20 to 28 percent passing the 4.75-mm sieve. The model limits the 4.75-mm size fraction to a maximum of 20 percent of particles having greater than a 3:1 length-to-thickness ratio and a maximum of 5 percent of particles having greater than a 5:1 length-to-thickness ratio. The model recommends that the Los Angeles (L.A.) abrasion weight loss of the aggregate should be a maximum of 30 percent. The model also advocates the use of an aggregate with a maximum water absorption of 2 percent. Decreasing the coarse aggregate content by increasing the suggested upper limit will reduce the amount of draindown mastic in SMA mixtures. However, the effect on SMA performances of decreasing the coarse aggregate content needs to be evaluated.

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OBJECTIVE

This paper documents Phase I of an FHWA study in which the effects of coarse aggregate content on the properties of SMA mixtures were determined. The objective of this phase was to determine the effect of coarse aggregate content on SMA draindown and performance in terms of rutting.

EXPERIMENTAL PROGRAM

To achieve the objective of this study, 12 SMA mixtures were tested. Two aggregates, three gradations, and two stabilizers were used.

Stabilizers

The two stabilizers were a cellulose fiber, Interfibe 230, and a polymer, Styrelf 1-D. The Interfibe was added at 0.3 percent by mixture mass, based on the recommendations of the supplier. Styrelf is an asphalt modified by the supplier with polymer and received in bulk form (*3*).

Asphalt

The asphalt used for preparing the mixtures with Interfibe was AC-20. This asphalt was used in Strategic Highway Research Program (SHRP) studies and was designated "ABC." The properties of AC-20 and Styrelf are presented in Table 1. Styrelf was significantly

TABLE 1 Physical Properties of the Binders

	Virgin Binder	Binder After Thin-Film Oven Test
AC-20 Binder (FHWA Code: B6090)		
Thin-Film Oven Test, percent loss		0.07
Penetration, 25 C (100g, 5s), 0.1 mm	87	60
Absolute Viscosity, 60C, dPa-s	2 042	4 349
Kinematic Viscosity, 135C, mm^2/s	480	660
Specific Gravity, 25/25C	1.038	
Solubility in Trichloroethyline, %	99.99	
Inorganic Material or Ash, percent	0.06	
Flash Point, COC, C	2.88	
	Styrelf Binder (FHWA Code: B-6096)	
Thin-Film Oven Test, percent loss		0.13
Penetration, 25 C (100g, 5s), 0.1 mm	51	39
Absolute Viscosity, 60C, dPa-s	40 958	126 826
Kinematic Viscosity, 135C, $\mu m^2/s$	2 260	3 463
Specific Gravity, 25/25C	1.026	
Solubility in Trichloroethyline, %	99.92	
Inorganic Material or Ash, percent	0.12	
Flash Point, COC, C	271	

stiffer than the AC-20 asphalt, according to capillary viscosities and penetration. The supplier modified a different AC-20 asphalt in formulating the Styrelf binder. (Note: The absolute viscosities of the Styrelf binder may not be correct. ASTM D2171 is valid for Newtonian flow, but many modified binders exhibit non-Newtonian flow at 60°C. The industry currently recommends ASTM D4957 for modified binders, but FHWA did not have the viscometer needed for the test.)

Aggregates

Crushed diabase and limestone aggregates were used in this study. The diabase was used in constructing dense-graded pavement sections tested by the accelerated loading facility at the Turner-Fairbank Highway Research Center (TFHRC). The limestone was used in the SHRP studies and was designated "RC." Aggregate properties are presented in Table 2.

Three different aggregate gradations were used. The gradations were designed to meet the SMA TWG aggregate gradation requirements and the German specifications, except for the percentages of material passing the 4.75- and 2.36-mm sieves. The three gradations were designated Gradations I, II, and III. The percent passing all sieves greater than 4.75 mm and smaller than 2.36 mm were equal for the three gradations. Gradations I, II, and III consisted of 80, 70, and 60 percent retained on the 4.75-mm sieve, respectively. The aggregate gradations are presented in Table 2 and illustrated in Figure 1.

The percent L.A. abrasion weight loss for the coarse fraction of the limestone was above the maximum percent recommended by the SMA TWG. The diabase aggregate satisfied the recommendation. Aggregates with different weight losses were included in this study to determine whether weight loss affects mixture performance.

The percent water absorptions for the three diabase gradations were below the recommended maximum of 2 percent; they were slightly greater than 1 percent. The percent water absorptions for the three limestone gradations ranged from 2.56 to 2.88 percent. This indicated that the limestone SMA mixtures would have high binder absorptions. The ramifications of not meeting the absorption specification are unknown, except that specified minimum binder contents for SMA mixtures based on mass will be easier to meet. Minimum binder contents should be based on volume. This specification was adopted from European practice, in which most aggregates have low water absorptions and absorption is a minor concern.

The percentage of aggregate particles having greater than 3:1 and 5:1 length-to-thickness, width-to-thickness, or length-to-width ratios were measured by mass and by number using 100 particles for each coarse aggregate size. The results are presented in Tables 3 and 4. The diabase aggregate did not meet the SMA TWG recommendations for flat and elongated particles in the coarse aggregate. Assuming that the recommendations are valid, there may be some breaking of the diabase aggregate particles in the hot-mixture plant or under traffic. The limestone aggregate met the recommendations.

Mixture Design

Marshall mix designs were performed to determine the optimum asphalt contents (OACs). The mixtures were designed to sustain

TABLE 2 Aggregate Properties

Sieve Size, mm	Gradation, Percent Passing			SMA Model Specification	Based on German Spec (FHWA-RD-92-006)
	I	II	III		
19.0	100.0	100.0	100.0	100.0	100.0
12.5	95.0	95.0	95.0	85-95	90-100
9.5	68.0	68.0	68.0	75 (maximum)	34-75
4.75	20.0	30.0	40.0	20-28	23-41
2.36	17.0	22.0	26.0	16-24	18-20
1.18	16.0	16.0	16.0		15-24
0.600	14.0	14.0	14.0	12-16	12-20
0.300	12.0	12.0	12.0	12-15	10-17
0.150	10.0	10.0	10.0		9-14
0.075	9.0	9.0	9.0	8-10	8-13

	Diabase Gradation			Limestone Gradation		
	I	II	III	I	II	III
Bulk Dry Sp. Gr.	2.827	2.823	2.843	2.506	2.513	2.526
Bulk SSD Sp. Gr.	2.861	2.865	2.873	2.578	2.586	2.591
Apparent Sp. Gr.	2.916	2.885	2.932	2.701	2.709	2.701
Percent Absorption	1.16	1.17	1.07	2.88	2.88	2.56

L.A. Abrasion of the Particles in the Predominate Size Fractions Above the 2.36-mm Sieve, Percent Weight Loss:

Diabase = 17.8
Limestone = 35.4

SSD: Saturated-surface dry.

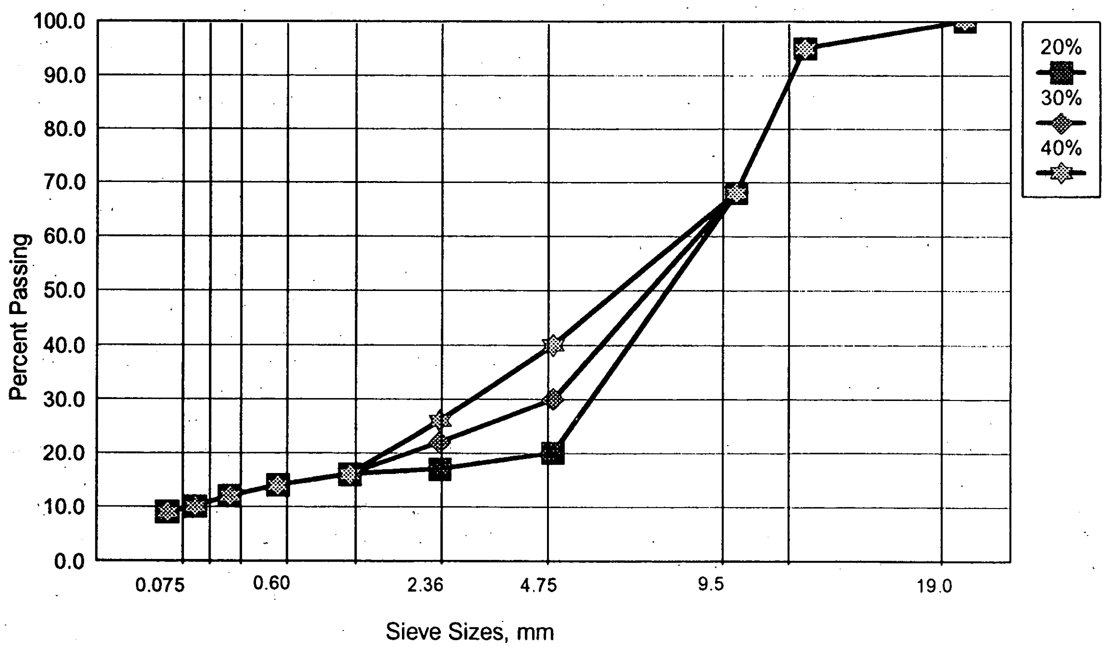

FIGURE 1 Aggregate gradations.

TABLE 3 Percent Flat and Elongated Particles

		Length to Thickness			
		5:1		3:1	
		By Mass	By Number	By Mass	By Number
Diabase	3/4 to 1/2	0.8	1	11.7	14
	1/2 to 3/8	2.3	4	25.3	28
	3/8 to #4	3.6	5	42.3	41
Limestone	3/4 to 1/2	0.0	0	11.9	14
	1/2 to 3/8	0.7	1	12.2	16
	3/8 to #4	5.3	8	23.8	29
		Width to Thickness (Flat)			
Diabase	3/4 to 1/2	0.0	0	2.0	3
	1/2 to 3/8	0.4	1	2.9	6
	3/8 to #4	0.0	0	4.5	6
Limestone	3/4 to 1/2	0.0	0	0.3	1
	1/2 to 3/8	0.0	0	1.7	3
	3/8 to #4	0.0	0	3.0	7
		Length to Width (Elongated)			
Diabase	3/4 to 1/2	0.0	0	0.0	0
	1/2 to 3/8	0.0	0	1.4	1
	3/8 to #4	0.0	0	1.3	1
Limestone	3/4 to 1/2	0.0	0	0.0	0
	1/2 to 3/8	0.0	0	0.0	0
	3/8 to #4	0.0	0	0.8	1

Note: Based on samples of 100 particles.

heavy traffic. SMA mixtures are designed in Europe for heavy traffic using 50 blows (*1*). Hence, the mixtures were compacted using 50 blows. The design air void content was 3.5 percent. The target mixing and compaction temperatures were 154°C and 143°C, respectively. Using three gradations (Gradations I, II, and III), two aggregates (diabase and limestone), and two stabilizers (Interfibe and Styrelf), 12 SMA mixtures were prepared.

The Styrelf mixture with diabase using Gradation I was eliminated from the rutting evaluation because of excessive draindown.

Draindown

The German draindown test, the FHWA draindown test for open-graded friction courses (OGFC), the 2.36-mm sieve draindown test developed in the Bituminous Mixtures Laboratory at TFHRC, and the National Center for Asphalt Technology (NCAT) draindown test were included in this study. These tests were performed to determine the effect of decreasing coarse aggregate content on draindown of the mastic, as well as the efficiency of the two stabilizers in preventing draindown.

In the German draindown test, 1 kg of mixture is prepared at the mixing temperature. The mixture is then placed into a tared, dried 800-mL glass beaker and weighed to the nearest 0.1 g. The beaker is then covered and stored for 60 min at 170°C. After storage, the mixture is removed from the beaker and placed in a tared bowl by quickly turning the beaker upside down without shaking. The final mass of the mixture is then measured and the percent draindown is calculated as

$$\text{Loss (percent)} = \frac{100\,(\text{initial sample mass} - \text{final sample mass})}{\text{initial sample mass}} \quad (1)$$

The storage temperature used in Germany is the hot-mix discharge temperature, which is much higher than temperatures used in the United States. Hence, the procedure was modified so that the compaction temperature of 143°C was used instead of 170°C.

The FHWA OGFC draindown test uses a clear Pyrex pie plate with a diameter of 203.2–228.6 mm. The mixture is placed on the Pyrex pie plate. The mixture and the plate are stored for 60 ± 1 min at 143°C. The degree of draindown is determined by comparing the amount of drained binder (viewed through the bottom of the plate) to five standard pictures having a scale of 1 to 5, representing no draindown to excessive drainage.

In the 2.36-mm sieve draindown test, a dried mixing bowl is weighed to the nearest 0.1 g. A dried 2.36-mm sieve of similar diameter is placed on top of the bowl, and 1 kg of asphalt mixture is placed on the 2.36-mm sieve immediately after mixing. The bowl,

TABLE 4 Flat and Elongated "Weighted Average" Based on Mass

Aggregate Type	Aggregate Gradation	Length to Thickness 5:1	Length to Thickness 3:1
Diabase	I	3.0	34.7
	II	2.9	33.5
	III	2.8	32.2
Limestone	I	3.4	19.1
	II	3.1	18.4
	III	2.8	17.6
		Width to Thickness	
Diabase	I	0.14	3.8
	II	0.15	3.7
	III	0.18	3.6
Limestone	I	0.00	2.4
	II	0.00	2.3
	III	0.00	2.2
		Length to Width	
Diabase	I	0.00	1.3
	II	0.00	1.2
	III	0.00	1.2
Limestone	I	0.00	0.5
	II	0.00	0.4
	III	0.00	0.4

sieve, and mixture are then covered with aluminum foil and stored for 60 ± 1 min at 143°C. After storage, the sieve is removed and the final mass of the bowl is obtained. The percent loss due to draindown is calculated as:

$$\text{Loss (percent)} = \frac{100\ (\text{final bowl mass} - \text{initial bowl mass})}{\text{initial sample mass}} \quad (2)$$

In the NCAT draindown test, the sample is placed in a wire basket that is positioned on a preweighed dry paper plate. The sample, basket, and plate are placed in a forced-air oven for 60 min at 143°C. After 60 min, the basket containing the sample is removed from the oven along with the paper plate, and the paper plate is weighed to determine the amount of draindown that occurred. The percent loss due to draindown is calculated as follows:

$$\text{Loss (percent)} = \frac{100\ (\text{final paper mass} - \text{initial paper mass})}{\text{initial sample mass}} \quad (3)$$

When this test was being performed, some particles of the mixture fell through the basket onto the paper plate. Those particles were put back into the basket before the basket was placed in the oven.

The SMA TWG recommendation of a maximum mass loss of 0.3 percent was applied to the German test, 2.36-mm sieve test, and the NCAT draindown test.

Rutting Evaluation

The French Laboratories des Ponts et Chaussees's pavement rutting tester, the Georgia loaded-wheel tester (GLWT), and the Hamburg wheel-tracking device were used to measure the rutting resistances of the mixtures.

French Pavement Rutting Tester

The French pavement rutting tester tests slabs with dimensions of 500 × 180 × 50 mm using a smooth, reciprocating, pneumatic rubber tire at 0.61 MPa and loading of 5,000 ± 50 N. The tire is 415 mm in diameter and 109 mm wide. A hydraulic jack under 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. The compaction effort used in this study should provide an air void level close to the low end of the air void range that can be obtained in the field after compaction by the rollers (*3*). After the slabs were fabricated, they were cured at room temperature for 2 days. Two slabs were fabricated at the OAC for each mixture.

An initial densification of 1,000 cycles at 25°C is first applied. A cycle is two passes of the tire. The thicknesses of the slabs are measured at the end of the initial densification. These readings are considered the zero readings. The slabs are then heated to the test temperature of 60°C for 3 hr before the test begins. For a 50-mm-thick slab, the test is performed to 3,000 cycles, and the average rut depths at 30, 100, 300, 1,000, and 3,000 cycles are measured. If the average rut depth at 3,000 cycles is more than 20 percent of the slab thickness, then the mixture is considered a failure and the test is stopped (*4*). To measure the average rut depth, the machine is stopped and 15 measurements on the slab are taken—five locations along the length and three locations along the width. Slopes for different mixtures taken from log rut depth versus log cycle plots can also be compared. Rut-susceptible mixtures generally have higher slopes.

For all the SMA mixtures tested, the average percent rut depth was less than 20 percent of the slab thickness at 3,000 cycles. Therefore, it was decided to extend the test to 10,000 cycles.

Georgia Loaded-Wheel Tester

The GLWT tests a beam with dimensions 381 × 76.2 × 76.2 mm for rutting at 40.6°C. The beams are prepared by compression. Densities within 97 percent of the Marshall design density are recommended (*5*). To achieve the recommended density, a 444.8-kN load was applied and released four times rapidly and then reapplied for 6 min.

Before testing, the beams were cured for 7 days at room temperature, then cured for 24 hr at 40.6°C. After curing, each beam was loaded into the testing frame of the GLWT and initial readings were taken at the center, 50.8 mm left of center, and 50.8 mm right of center across the length of the beam. A rubber hose inflated to 0.69 MPa is positioned across the sample and a loaded wheel runs back and forth on the top of the rubber hose. When the wheel moves from right to left, the load is approximately 740 N at the center of the beam, while it is 630 N when moving left to right. The test was performed for 8,000 cycles. One cycle is defined as two passes of the wheel. Final readings were taken at the same positions as the initial readings . If the average rut depth exceeds 7.6 mm, the mixture is considered to have failed (*5*). Two beams were fabricated at the OAC for each mixture.

Hamburg Wheel-Tracking Device

The Hamburg wheel-tracking device was used to test slabs that have dimensions of 320 × 260 × 80 mm, using a smooth, reciprocating solid steel wheel. The wheel has a diameter of 203.5 mm and a width of 47.0 mm. The load is 710 N. Slabs are submerged and tested in water at 50°C. The machine has two steel wheel assemblies and tests two slabs simultaneously. The slabs were fabricated using a steel wheel roller. The slabs were cured at room temperature for 2 days. After curing, the slabs were placed in the device, and the device was filled with water until the slabs were completely immersed. When the water temperature reached 50°C, the slabs stayed immersed for 45 min before the test was performed. The machine is automated and records the deformation after each cycle. The test is performed for 20,000 passes (10,000 cycles).

The data analysis from the Hamburg wheel-tracking device includes the post-compaction consolidation, creep slope, stripping inflection point, and stripping slope as shown in Figure 2 (*6*). The post-compaction consolidation is the deformation at 1,000 passes. It is known as post-compaction consolidation because the wheel is assumed to be compacting the mixture within the 1,000 passes. The creep slope is (a) a measure of accumulation of permanent deformation caused primarily by mechanisms other than moisture damage, (b) the inverse of the rate of deformation in the linear region of the curve after post-consolidation has ended and before the stripping inflection point, and (c) the number of passes required to create a 1-mm rut depth. The stripping inflection point is the number of passes at the intersection of the creep slope and the stripping slope. It is the number of passes required to initiate stripping. The stripping slope is (a) a measure of the accumulation of permanent deformation due primarily to moisture damage, (b) the inverse of the rate of deformation after the stripping inflection point, and (c) the number of passes required to create a 1-mm rut depth from stripping (*7*).

In this study, the creep slope was measured to compare mixtures in terms of their rutting susceptibility. A higher creep slope indicates less rutting.

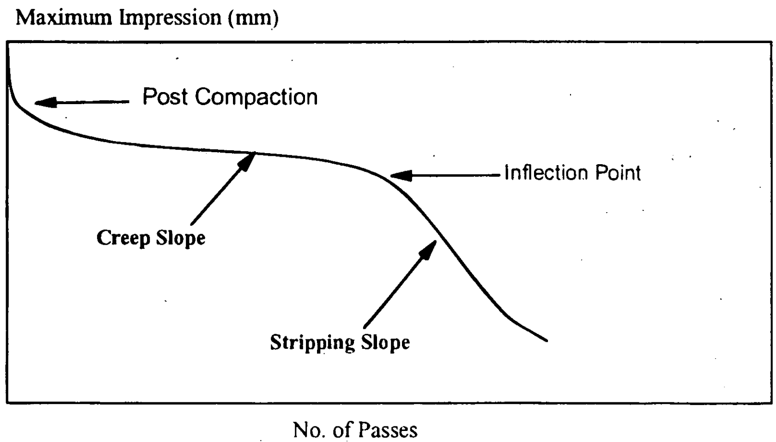

FIGURE 2 Data analysis of the results from the Hamburg Wheel-Tracking device.

RESULTS AND ANALYSIS

Mixture Design

The Marshall mixture design results are presented in Table 5. For the same gradation, the Interfibe and Styrelf mixtures with limestone had similar OAC. Also, for the same gradation the OAC of the Interfibe and Styrelf mixtures with diabase were close. There was a trend for increasing binder content and voids in mineral aggregate (VMA) with an increase in coarse aggregate. A decrease in stability and an increase in the voids filled with asphalt (VFA) were associated with this trend. The flow increased with an increase in coarse aggregate content, except for the Interfibe mixture with limestone using Gradation I. The flow and stability values were higher for Styrelf mixtures than for Interfibe mixtures. The percent binder increased more when the coarse aggregate content was increased from 70 to 80 percent than when it was increased from 60 to 70 percent. The VMAs of each SMA did not vary with the binder content, and the air voids versus binder content relationships were generally linear. Only three binder contents were used in designing the SMA mixtures.

The SMA TWG recommends a minimum of 6 percent binder by mass of mixture (*2*). Table 5 shows that increasing the coarse aggregate content increased the optimum asphalt content of the SMA mixtures.

The SMA TWG recommends a minimum VMA of 17. All diabase mixtures satisfied this recommendation, whereas none of the limestone mixtures did. In an associated study that is evaluating the same mixtures, extractions were performed to determine whether the Marshall hammer broke the aggregates. The extraction results showed that the increase in the amount passing the 4.75-mm sieve was higher for the limestone aggregate than for the diabase aggregate (Stuart and Mogawer, in a paper in this Record). This is due to the high L.A. abrasion weight loss of the limestone aggregate. The limestone L.A. abrasion weight loss was 35.4 percent. (The maximum recommended by the SMA TWG is 30 percent.) Because the limestone aggregate particles fractured more than the diabase particles, it was hypothesized that the lower VMAs of the

TABLE 5 Mixture Design Properties

	Diabase			Limestone		
	I	II	III	I	II	III
Interfibe Mixtures						
OAC, by mass	7.5	6.3	5.7	6.7	5.7	5.6
OAC, % by volume	17.6	15.1	13.8	14.5	12.6	12.3
Eff OAC, % by volume	16.7	14.1	13.3	12.5	10.9	10.6
Air Voids, %	3.5	3.5	3.5	3.5	3.5	3.5
VAM, %	20.2	17.7	16.8	16.1	14.4	14.0
VFA, %	80.2	80.2	79.3	78.3	75.8	75.2
Flow, 0.25 mm	17.7	17.7	14.7	18.1	19.8	17.4
Stability, N	7 819	7 819	9 000	7 633	8 404	10 498
Styrelf Mixtures						
OAC, % by mass	8.4	6.6	6.2	6.8	5.7	5.5
OAC, % by volume	19.5	15.6	14.7	14.7	12.6	12.2
Eff OAC, % by volume	18.5	14.7	13.9	12.8	10.8	10.5
Air voids, %	3.5	3.5	3.5	3.5	3.5	3.5
VMA, %	22.2	18.4	17.6	16.4	14.4	14.0
VFA, %	84.2	81.0	80.2	78.7	75.8	75.1
Flow, 0.25 mm	31.4	28.3	27.6	25.2	24.1	22.9
Stability, N	8 756	10 337	13 390	9 547	12 094	12 193

OAC: Optimal Asphalt (Binder) Content.
Eff OAC: Effective Optimum Asphalt (Binder) Content.
VMA: Voids in the Mineral Aggregate.
VFA: Voids Filled with Asphalt.

limestone mixtures were due to the greater amount of broken aggregate.

Draindown

The draindown data are presented in Table 6. It was observed that the coarse aggregate content had no effect on the draindown of mixtures prepared using Interfibe as the stabilizer, whereas mixtures prepared with Styrelf drained severely at the high coarse aggregate content (Gradation I). The six mixtures with Interfibe had low amounts of draindown and passed the four draindown tests. For mixtures prepared with either aggregate and Styrelf as a stabilizer, the German test, the 2.36-mm sieve test, and the NCAT test showed that Gradations II and III had less draindown than Gradation I.

It also was observed that the results from the four tests do not always agree.

Rutting Evaluation

French Pavement Rutting Tester

The percent air voids of the slabs are presented in Table 7. First, trial slabs were prepared and their overall air voids were measured. Then the trial slabs were cut along the wheel path, and the air voids in the wheel path were measured. This was done to determine the air voids in the wheel path before testing because they are always lower than the overall air voids. The initial air voids in the wheel path cannot be measured for the slabs to be tested.

The slabs to be tested were then prepared and their overall air voids were measured. After testing they were cut along the wheel path and their air voids in and out of the wheel paths were measured. Following the compaction sequence recommended by the manufacturer, the Interfibe and Styrelf mixtures with diabase had lower overall air voids than the Interfibe and Styrelf mixtures with limestone. The reason for this could be that the high amount of flat and elongated particles in the diabase become horizontally aligned during compaction. For the Interfibe mixtures the decreases in air voids during testing ranged from 0.4 to 2.1 percent, but there were no trends with increasing coarse aggregate content. For the Styrelf mixtures the decreases in air voids were not greater than the variability of air voids before testing. Therefore, whether the air voids decreased during testing could not be determined. It is often very difficult to obtain the desired air void level using the French compactor.

The percent rut depths are presented in Table 7. The percent rut depths of all the mixtures at the different number of passes were less than 20 percent of the specimen's thickness. Hence, all the mixtures passed.

The analysis of variance (ANOVA) statistical method at a 0.05 level of significance showed that aggregate gradation had no significant effect on the percent rut depths at 3,000 and 10,000 cycles.

TABLE 6 Draindown Test Results

	Diabase			Limestone		
	I	II	III	I	II	III
Interfibe Mixtures						
German Test, % mass loss	0.15	0.08	0.05	0.04	0.04	0.07
FHWA OGFC Test, draindown level	3	2	1	2	1	1
2.36-mm Sieve Test, % mass loss	0.00	0.00	0.00	0.00	0.00	0.00
NCAT Test, % mass loss	0.04	0.03	0.01	0.03	0.01	0.01
Styrelf Mixtures						
German Test, % mass loss	22.20	2.84	0.84	2.81	0.37	0.12
FHWA OGFC Test, draindown level	5	5	4	5	3	2
2.36-mm Sieve Test, % mass loss	8.40	1.45	0.00	3.20	0.01	0.00
NCAT Test, % mass loss	6.20	0.44	0.44	0.42	0.18	0.08

TABLE 7 (*a*) Percent Air Voids for French Pavement Rutting Tester Slabs; (*b*) French Pavement Rutting Tester Results

a)

	Diabase			Limestone		
	I	II	III	I	II	III
Interfibe Mixtures						
Overall Slab:						
Trial Specimen	4.52	4.05	5.22	5.48	4.99	6.32
Test Specimens	4.26	4.12	4.84	4.68	5.41	5.90
In Wheel Path:						
Trail Specimen	4.13	2.63	3.48	4.99	4.19	5.28
Test Specimens	2.02	2.22	2.45	3.08	3.16	3.63
Styrelf Mixtures						
Overall Slab:						
Trial Specimen	NT	2.46	1.86	4.84	5.10	4.95
Test Specimens		3.51	3.00	4.26	3.47	3.78
In Wheel Path:						
Trial Specimen		0.66	0.70	3.57	3.55	3.36
Test Specimens		1.14	1.12	2.41	1.59	1.86

b)

	Diabase			Limestone		
	I	II	III	I	II	III
Interfibe Mixtures						
% Rut Depth @ Cycle:						
30	1.3	2.1	1.2	1.2	1.5	1.0
100	2.2	2.8	1.8	1.9	2.2	1.5
300	3.4	3.3	2.4	2.4	3.1	1.9
1000	4.2	4.0	3.1	3.4	3.7	2.9
3000	5.1	4.9	4.2	5.1	4.8	3.7
10000	7.6	7.9	5.9	7.2	7.5	5.7
Slope	0.29	0.21	0.27	0.29	0.26	0.29
Styrelf Mixtures						
% Rut Depth @ Cycle:						
30	NT	3.0	3.5	1.2	2.5	2.8
100		3.7	4.6	1.4	4.2	3.5
300	NT	4.1	5.4	2.2	5.1	4.4
1000		4.9	6.4	3.1	6.3	5.3
3000		5.3	7.0	3.8	7.5	6.8
10000		6.3	7.5	5.1	9.1	7.8
Slope	0.12	0.13	0.26	0.21	0.18	1.86

NT: Not Tested.

Statistically, mixtures prepared with Styrelf had significantly lower rates of rutting than mixtures prepared using Interfibe, but the rut depths were not statistically different.

Georgia Loaded-Wheel Tester

The rut depths and air voids are presented in Table 8. The rut depths for all mixtures were less than 7.6 mm. Therefore, all of the mixtures passed.

The ANOVA statistical method at a 0.05 level of significance showed that aggregate gradation had no significant effect on the rut depth of the mixtures. Mixtures with Styrelf had significantly lower rut depths than mixtures with Interfibe.

Hamburg Wheel-Tracking Device

The creep slopes are presented in Table 9. The limestone Gradation I mixtures failed at fewer than 3,000 passes when either Interfibe or

TABLE 8 Georgia Loaded-Wheel Results

	Diabase			Limestone		
	I	II	III	I	II	III
Interfibe Mixtures						
Rut Depth, mm	6.5	5.3	4.6	4.8	3.6	4.1
Air Voids, %	3.3	4.4	3.4	4.6	3.8	4.7
Styrelf Mixtures						
Rut Depth, mm	NT	3.3	3.0	4.1	3.4	2.8
Air Voids, %		3.3	3.3	3.8	4.1	3.4

NT: Not Tested.

TABLE 9 Hamburg Wheel-Tracking Results

	Diabase			Limestone		
	I	II	III	I	II	III
Interfibe Mixtures						
Creek Slope, passes	1077	1866	1679	24.3	NT	NT
Air Voids, %	6.2	4.7	4.9	4.2		
Styrelf Mixtures						
Creep Slope, passes	NT	8333	7671	902	NT	NT
Air Voids, %		5.1	4.4	5.1		

NT: Not Tested.

Styrelf was used as the stabilizer. The steel wheel of the device crushed the limestone, causing the mixture to fail quickly. Gradations II and III were not tested because of the high amount of aggregate crushed. Statistically, gradation had no effect on the creep slopes of the Interfibe or the Styrelf mixtures with diabase. The mixtures with Styrelf had significantly higher creep slopes than the mixtures with Interfibe.

CONCLUSIONS

Mixture Design

- The air voids versus binder content relationships were generally linear for each mixture.
- The VMAs of each mixture did not vary with binder content during the mixture design.
- All diabase mixtures satisfied the SMA TWG recommendation for VMA (minimum of 17), but none of the limestone mixtures did. It was hypothesized that the lower VMAs and effective binder content by volume were due to a greater amount of aggregate being broken during compaction. However, the VMAs for the limestone mixtures were close to 17 when the coarse aggregate content was 80 percent.
- There was a trend for increasing binder content, VMA, and VFA with increasing coarse aggregate content. Associated with this trend was a decrease in stability.
- The optimum binder contents of the mixtures increased more when the coarse aggregate content increased from 70 to 80 percent than when it was increased from 60 to 70 percent.

Draindown

- The SMA mixtures with Styrelf had higher amounts of mastic draindown than the SMA mixtures with Interfibe.
- Coarse aggregate content had no effect on the draindown of mixtures prepared with Interfibe.
- Mixtures with Styrelf drained severely at high coarse aggregate content.
- The data from the German draindown test, the FHWA draindown test for OGFC, the FHWA 2.36-mm sieve draindown test developed at TFHRC, and the NCAT draindown test did not always agree.

Rutting

- Based on the GLWT and the Hamburg wheel-tracking device, the mixtures with Styrelf had significantly lower rut depths than the mixtures with Interfibe. Based on the French pavement rutting tester, the mixtures with the Styrelf had significantly lower rates of rutting (slopes) than the mixtures with Interfibe, but the rut depths were not statistically different.

- Based on the French pavement rutting tester, GLWT, and the Hamburg wheel-tracking device, decreasing the coarse aggregate content from 80 to 60 percent had no significant effect on the rutting performance of the mixtures.

RECOMMENDATIONS

- Increasing the gap in the gradation should reduce the effects on performance of fluctuations in hot-mix plant binder contents. These effects may vary with gradation. This aspect is very important, but was not included in this study. Additional research is needed in this area.
- The diabase aggregates had more flat and elongated particles than recommended by the SMA TWG. Nevertheless, the SMA mixtures prepared with these aggregates passed the tests for rutting. Therefore, additional research on the effects of flat and elongated coarse aggregate particles on the rutting susceptibilities of SMA mixtures is needed. This should include the use of various percentages of flat and elongated particles.
- The four draindown tests did not always agree. Therefore, to determine the most applicable test, it is recommended that more SMA mixtures be tested using the four tests, and that the data be correlated to field performance.

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