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STONE SKELETON ASPHALT: CONCEPT EVALUATION

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TABLE OF CONTENTS

ABSTRACT

A study to evaluate a stone matrix asphalt (SMA)- like asphalt mixture termed "stone skeleton asphalt" was conducted. The concept of stone skeleton asphalt was a mixture that would have similar performance characteristics to typical SMA mixtures, but without the elements contained in SMA mixtures that increase its cost. These elements include: modified asphalt binders, fibers, and mineral fillers. A 19.0 mm nominal maximum aggregate size (NMAS) limestone/granite blend SMA was used as a control mixture, from which cost increasing elements were systemically removed to assess their influence on volumetrics, draindown, and performance. Performance tests included resistance to rutting and falling-head permeability testing.

Results from the volumetric, draindown, and performance testing were gathered and analyzed. From these results, several conclusions were made. One, the inclusion of fibers increased the mixture's voids in mineral aggregate (VMA) and optimum asphalt content. Two, in terms of draindown, the absence of fibers did increase the amount of draindown compared to the mixtures with fibers included, but did not exceed the maximum specified limit. Three, the rutting results from the mixtures containing performance grade (PG) 67-22 and fibers, and particularly the additional percentage of fly ash, indicated similar results to those of the mixtures with a modified PG 76-22 asphalt binder. And four, at typical in-place densities, stone skeleton mixtures appear to be permeable. Densities would have to be near 95 percent of maximum theoretical density to produce an impermeable pavement. The potential impacts on the mixtures durability were not evaluated in this study.

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INTRODUCTION

A study was conducted to evaluate the concept of stone skeleton asphalt. The stone skeleton mix concept was proposed to produce a more economical stone matrix asphalt (SMA)-like mix which would also allow better utilization of aggregate size fractions. This study initially focused on the elements of SMA, which increase its cost. Elements which add cost to SMA as compared to dense-graded mixes may include: the use of fiber, the addition of mineral filler, and the use of polymer modified binders. Therefore, a standard SMA mixture utilizing a limestone/granite aggregate source, fly-ash mineral filler, cellulose fiber, and polymer modified performance grade (PG) 76-22 binder was used as a base line. Various elements which add cost were then systematically removed from the mixture and the performance of the resulting mixture measured. For example, a mixture with a stone skeleton would be expected to be resistant to rutting since the stone skeleton carries the load. Rutting comparisons were made between a mixture with the standard climatic grade of binder PG 67-22 and a mixture produced with PG 76-22. Similarly, fiber is added to an SMA mixture to prevent draindown of the binder during construction. However, it may be possible to prevent draindown by use of a polymer modified binder or by altering the mineral filler content.

In Europe, fractionated aggregate is generally used to produce HMA and in particular SMA. Fractionated aggregate is separated into very narrow size ranges. For instance, in Germany aggregates may be fractionated into the following sizes: < 2, 2-5, 5-8, and 8-11 mm. One criticism of many SMA and some Superpave mixes is that they do not uniformly use the range of crushed aggregate sizes produced and that this can result in aggregate producers accumulating large stockpiles of crushed fine aggregates (*1*). It has been proposed that if contractors were allowed to produce a stone skeleton mix, using a variety of fractionated aggregate sizes, those aggregates could be used more efficiently (*2*, *3*).

The objective of this study was to perform a laboratory evaluation of the stone skeleton asphalt concept. Elements of SMA (polymer modified binder, fiber, and mineral filler) were systematically removed to assess their effect on performance. The goal of the study was to develop a draft specification for stone skeleton asphalt which would provide performance similar to SMA at a reduced cost.

RESEARCH APPROACH

An experimental plan was developed to investigate potential options to reduce the cost of an SMA type mix (Table 1). PG 67-22 was selected for the non-modified binder. PG 67-22 is a grade commonly used in the southeastern United States. The high temperature binder properties of PG 67-22 are tested at 67C. This binder also typically meets all the requirements of a PG 64-22 and is approximately equivalent to an AC-30. The control mixture was a 19.0 mm nominal maximum aggregate size (NMAS) SMA mixture produced with a blend of limestone and granite aggregates. The mix is normally used on interstate routes underneath an open-graded friction course. The mixture is produced with polymer-modified PG 76-22, 0.3 percent cellulose fibers

Table 1. Experimental Matrix

Mix	PG 76-22	PG 67-22	Fiber	Fly Ash
Control (SMA)	X		X	2%
1		X	X	2%
2	X			2%
3		X		2%
4		X		4%

and 5 percent fly ash. The fly ash was reduced from 5 to 2 percent in the laboratory to increase voids in mineral aggregate (VMA). The control mix was altered as shown in Table 1 to assess the effect of various components (modified binder, fiber, and mineral filler) on performance. The stockpile percentages and blend gradations are shown in Table 2.

The optimum asphalt content of the SMA control mixture was verified using the Superpave gyratory compactor (SGC) with samples compacted using N_{design} = 65 gyrations. The same laboratory compactive effort was used for all of the mixtures. Samples were prepared at four asphalt contents in 0.5 percent increments ranging from 4.5 to 6.0 percent for the mixtures containing fibers and from 4.0 to 5.5 percent for the mixtures without fibers. Six replicate samples were prepared at each asphalt content. The bulk specific gravities of the compacted samples were determined according to AASHTO T166.

Due to the high asphalt content of SMA mixtures, draindown can be a concern. Draindown is the condition where the asphalt binder drains to the bottom of the silo or haul truck prior to placement. Draindown is primarily a construction concern. “Fat” or binder rich areas should perform satisfactorily; however, the corresponding low asphalt areas may have long-term durability concerns.The prevalence of fat spots on an SMA pavement is typically higher if fibers are not used, even with mixes which meet the draindown requirements.

Cellulose or mineral fibers are typically added to SMA at a rate of approximately 0.3 percent by total weight of mix to prevent draindown. A specialized fiber feeder is generally required to add the fibers. Draindown potential was tested according to AASHTO T305. Draindown for each mixture was generally assessed at optimum asphalt content and three additional asphalt contents (4.5, 5.0, and 5.5 percent) and at three temperatures. The maximum allowable draindown is typically specified as 0.3 percent by total weight of mix. The draindown test temperatures were adjusted between 250 and 350F (121 and 177C) in 50F (28C) increments to try and bracket the temperature at which the draindown exceeded 0.3 percent.

The rutting potential of the mixes was measured with the Asphalt Pavement Analyzer (APA) using the methodology recommended in NCHRP 9-17, “Accelerated Laboratory Rutting Tests: Asphalt Pavement Analyzer.” The samples were tested at 67C (152.6F) with a 120 lb vertical load and 120 psi hose pressure. The samples were tested at their N_{design} air void content.

Falling-head permeability tests were performed over a range of air void contents to try and assess the required density to prevent permeability. The permeability tests were performed in accordance with ASTM PS 129-01.

Table 2. Mixture Gradations

Aggregate	Blend Percentages		
	Original JMF	Control and Blends with 2% Fly Ash	Blend 4 with 4% Fly Ash
LMS 57's	30	37	37
LMS 78's	44	47	45
Granite M-10's	10	13	13
Fly Ash	5	2	4
Baghouse Fines	1	1	1
RAP	10	0	0
Sieve, mm	Percent Passing		
25.0	100	99	99
19.0	90	89	89
12.5	74	70	70
9.5	54	51	52
4.75	28	22	25
2.36	21	17	20
1.18	17	14	17
0.600	15	12	15
0.300	11	10	13
0.150	9	8	11
0.075	8.0	6.2	8.8

RESULTS AND DISCUSSION

Volumetric Properties

The mixture volumetric properties as a function of binder content are shown in Table 3. Optimum asphalt contents were selected at 4 percent air voids. As expected, the mixtures containing fibers have higher optimum asphalt contents. This is due to the increased surface area of the fibers and their “blotting” effect, evident in Figure 1. What was unexpected, however, was the increase in voids in mineral aggregate (VMA) observed for the mixtures containing fibers (Figure 2). The optimum asphalt content is indicated in Figure 2 for each mixture.

Table 3. Mixture Volumetric Properties

Mix	Asphalt Content, %											
	3.5				4.0				4.5			
	Air Voids %	VMA %	VFA %	VCA %	Air Voids %	VMA %	VFA %	VCA %	Air Voids %	VMA %	VFA %	VCA %
PG 76-22 Fiber (Control)	NA				NA				6.5	16.6	61	35.4
PG 67-22 Fiber	NA				NA				6.7	16.8	60	35.6
PG 76-22 No Fiber	NA				5.6	14.6	62	33.9	4.5	14.7	69	34.0
PG 67-22 No Fiber	NA				5.3	14.5	63	33.8	5.2	15.4	66	34.6
PG 67-22 No Fiber 4% Fly Ash	5.3	13.8	60	33.2	4.0	13.7	71	33.2	3.2	13.8	77	33.5

Mix	Asphalt Content, %												Opt. AC%
	5.0				5.5				6.0				
	Air Voids %	VMA %	VFA %	VCA %	Air Voids %	VMA %	VFA %	VCA %	Air Voids %	VMA %	VFA %	VCA %	
PG 76-22 Fiber (Control)	5.2	16.5	68	35.4	4.0	16.6	76	35.5	3.0	16.8	82	35.6	5.5
PG 67-22 Fiber	5.6	16.9	67	35.8	4.3	16.9	75	35.7	3.1	16.9	82	35.7	5.6
PG 76-22 No Fiber	4.0	15.4	74	34.5	3.2	15.8	80	34.8	NA				5.0
PG 67-22 No Fiber	3.9	15.5	75	34.6	2.4	15.3	84	34.5	NA				5.0
PG 67-22 No Fiber 4% Fly Ash	2.6	14.1	82	34.0	NA				NA				4.0

NA = Not Tested
Each result represents the average of six samples.

Figure 1. Sample with Fiber (Right) and without Fiber (Left) at Optimum AC%

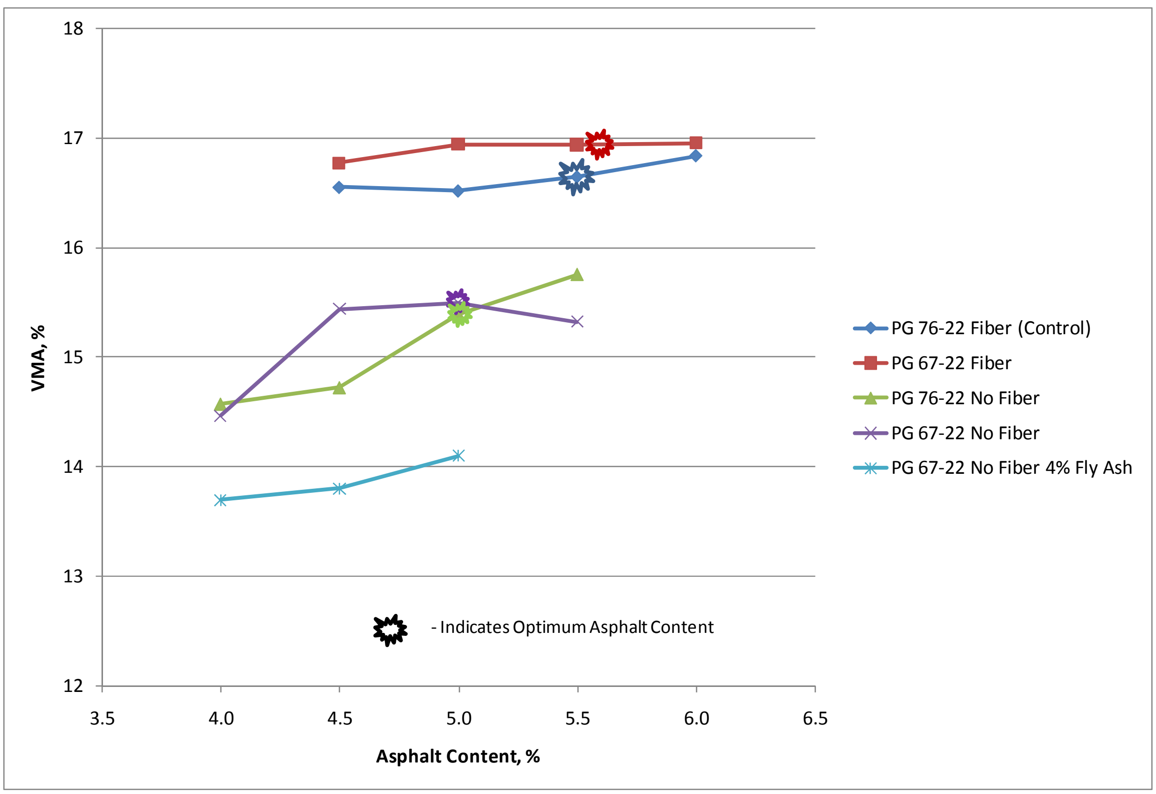

Figure 2. VMA versus Asphalt Content

The VMA for the two mixes containing fibers were both close to the 17 percent minimum typically specified for SMA. The VMA of the two mixes produced with an identical gradation, but without fibers, decreased by approximately 1.3 percent. As expected, the addition of 2 percent mineral filler further reduced the VMA at optimum asphalt content by an additional 1.7 percent. There are relatively small differences in VMA between the mixes produced with PG 67-22 and PG 76-22. Generally, at 4 percent air voids, VMA appears to be increasing above its minimum or is on the "wet" side of the VMA curve, with the exception of the PG 67-22 mix with 4 percent fly ash.

The concept of voids in coarse aggregate (VCA) was developed to ensure stone-on-stone contact in SMA type mixes (*4*). First, the VCA of the dry rodded condition (DRC) is determined using the coarse aggregate fraction. For a 19.0 mm (3/4 inch) NMAS mix, the coarse aggregate fraction is defined as the material retained on the 4.75 mm (No. 4) sieve. The coarse aggregate fraction is dry rodded in three lifts in a unit weight bucket and the voids between the coarse aggregate particles determined. The void space between the coarse aggregate in a compacted HMA sample can be calculated and is termed the VCA_{Mix}. Since only coarse aggregate particles are used when calculating the VCA_{DRC}, they represent a condition where stone-on-stone contact is assured. If the $VCA_{Mix} < VCA_{DRC}$ then there should be stone-on-stone (coarse aggregate) contact in the compacted mix samples, creating a "stone skeleton." The VCA_{DRC} was determined to be 41.3 percent. All of the VCA_{Mix}, shown in Table 3, are less than this value, indicating that all of the mixes achieved a stone skeleton.

Draindown

Fibers are included in an SMA mixture to prevent draindown. However, their inclusion also increases VMA, and therefore asphalt content and cost. If the stone skeleton mix was still durable with a lower minimum VMA and could be produced without draindown, the cost of the stone skeleton mix would be reduced.

The draindown results at optimum asphalt content are shown in Figure 3 as a function of temperature. Three replicates were evaluated at each temperature. A maximum draindown of 0.3 percent is typically specified at the anticipated plant production temperatures. All of the mixtures met this requirement at 350F (177C). As expected, the draindown was less for the mixtures containing fibers. However, the draindown for the mixture containing PG 76-22 without fibers at 350F increased only slightly (0.02 percent). Draindown would not be expected to decrease with increasing temperature. Additional 2 percent fly ash was added to one of the PG 67-22 mixtures without fibers (4 percent fly ash, total). This was done both to assess the effects of increased mineral filler on the draindown characteristics and rutting susceptibility. The additional mineral filler, in this case a fly ash, resulted in a minimal, if any, reduction in draindown.

A one-way ANOVA was conducted to compare the draindown results at 350F (177C) for the various mixes at optimum asphalt content. The ANOVA indicated that the draindown results

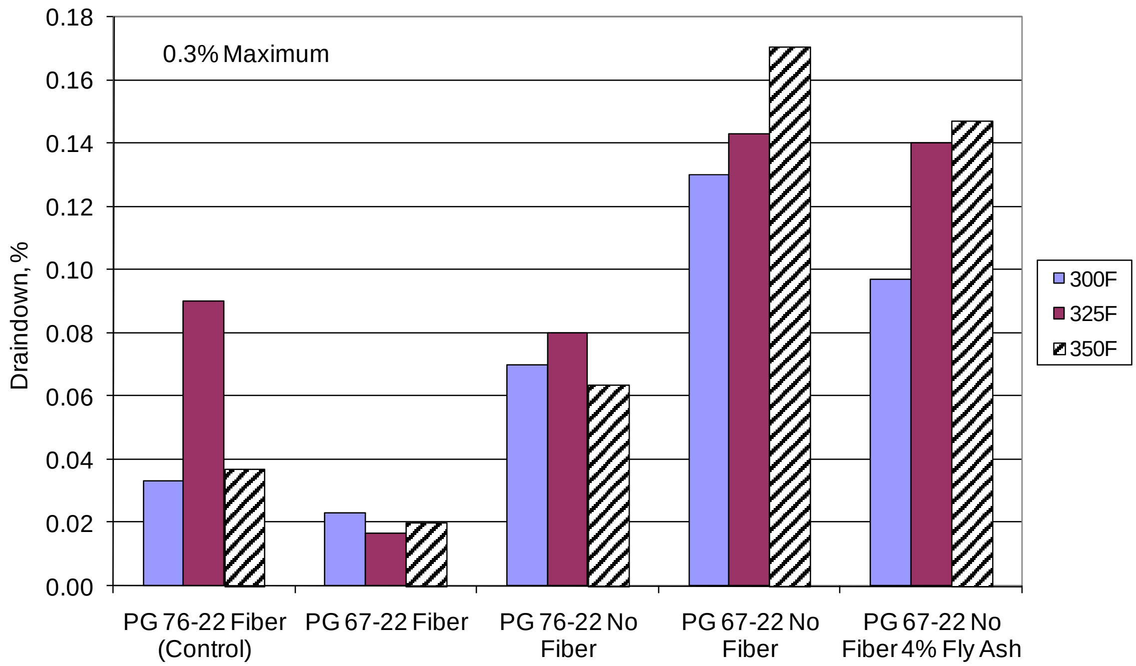

Figure 3. Draindown at Optimum Asphalt Content as a Function of Temperature

were significantly different (*p-value* = 0.000004). A Duncan's Multiple Range Test was then performed to determine which mixes had homogeneous means (5). The results indicated two groupings. The group with the least draindown included: PG 76-22 Control with fiber, PG 67-22 with fiber, and PG 76-22 without fiber. The group with significantly greater draindown included the two PG 67-22 mixes without fiber. However, it should be noted that both PG 67-22 mixes without fibers met the maximum draindown criterion of 0.3 percent.

APA Rut Depths

Figure 4 shows the average APA rut depths as a function of asphalt content. The optimum asphalt content of each mixture is indicated in the figure. The stone on stone contact in an SMA or stone skeleton mixture is designed to provide rut resistance. Both mix types should be less sensitive to rutting with increasing binder content as long as the mastic doesn't push the coarse aggregate skeleton apart. This insensitivity to asphalt content is generally evident in Figure 4. It was theorized that mixes with a stone skeleton may also be less sensitive to binder stiffness. For the PG 67-22 mixes, both the presence of fibers and additional mineral filler appear to reduce rutting potential. Fibers used in SMA are not generally considered to be stabilizers in terms of reducing rutting potential. However, the cellulose fibers used in this study appear to reduce rutting potential, even at higher optimum asphalt content. The mixture with 4 percent (2 percent additional) fly ash produced rut depths which were similar to the mixes containing PG 76-22. This is most likely due to the filler's stiffening effect on the mastic.

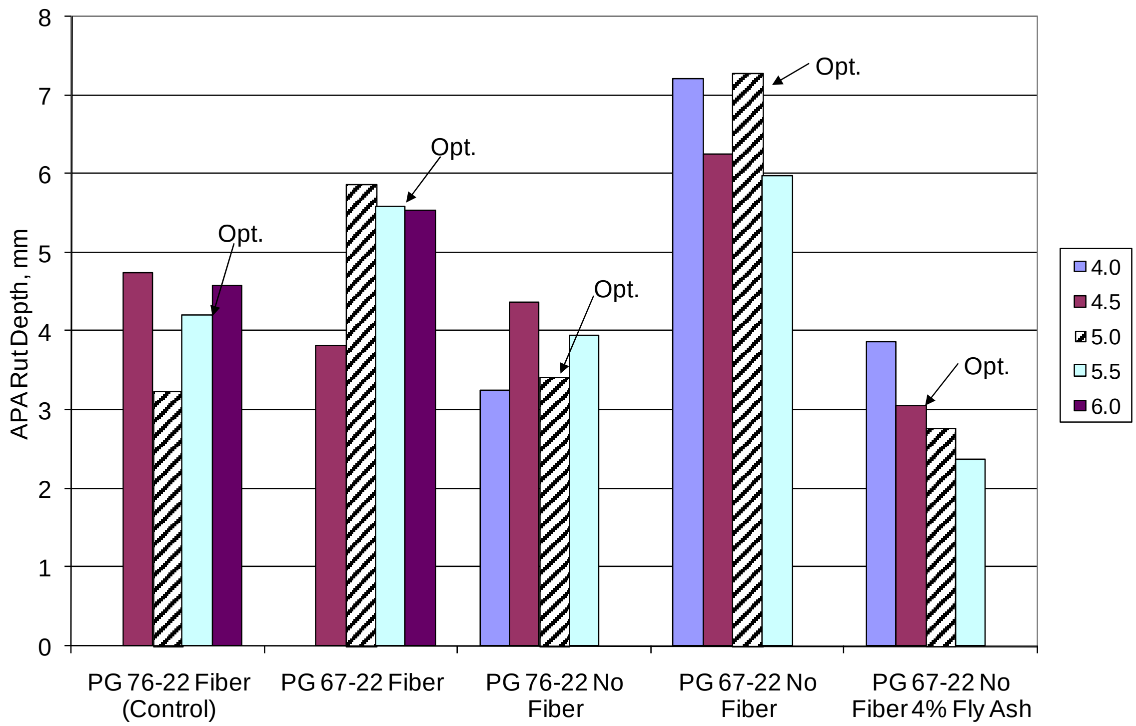

Figure 4. APA Rut Depths as a Function of Binder Content

Analysis of variance (ANOVA) was performed with Minitab statistical software using the General Linear Model. Binder content, PG grade, fiber content, fly ash content, and the interaction between PG grade and fiber content were used as factors for rut depth. The results are shown in Table 4. Binder content was not significant. This was expected since the VCA tests indicated a coarse aggregate stone skeleton. PG Grade was a significant factor, even though the mixes had a stone skeleton. The inclusion of fiber, by itself, was not significant; however, the interaction between PG Grade and the inclusion of fiber was significant. The presence of fiber in the PG 67-22 mix appears to have

Table 4. APA Rut Depth ANOVA

Source	Degrees of Freedom	Adjusted Sum of Squares	F-Statistic	*p-value*	Percent Contribution	Significant ?[1]
Binder Content	5	8.39	0.45	0.813	1.4	No
PG Grade	1	92.85	24.88	0.000	15.2	Yes
Fiber	1	6.74	1.81	0.182	1.1	No
Filler	1	154.04	41.27	0.000	25.1	Yes
PG *Fiber	1	22.17	5.94	0.016	3.6	Yes
Error	110	410.55			67.0	
Total	119	612.80				

[1] Indicates significance at the 5 percent level.

reduced rutting. The addition of 2 percent additional fly ash was also significant, reducing the measured rut depths to levels comparable to the PG 76-22 mixes. The large contribution of the error term indicates the factors considered did not explain the majority of the variation in measured rut depths.

A second ANOVA was run to compare the rut depths at optimum asphalt content. The rut depths from the different mixes were significantly different (*p-value* = 0.0024). A Duncan's Multiple Range test was used to identify the mixes with homogeneous rut depths (5). The PG 76-22 mixes with and without fiber and the PG 67-22 mix with 4 percent fly ash had the best rutting performance (Grouping A). The PG 67-22 mix without fiber had the worst rutting performance (Grouping B). The PG 67-22 mix with fiber was not significantly different from either group (Group AB).

Permeability Tests

Samples of the five mixes were produced at a range of air void contents using the SGC. The sample height was 3 inches (75 mm) or a thickness /NMAS of 4.0. The samples were tested for falling head permeability according to ASTM PS 129-01. The results, shown in Figure 5, indicate that the permeability of the SMA control and stone skeleton mixes increase rapidly with increasing sample air voids. Logarithmic regressions were used to predict the permeability at two commonly specified density levels as well as the density level required to achieve a permeability of 125 x 10^{-5} cm/sec, a level identified as separating permeable and impermeable mixes (6). The results are shown in Table 5.

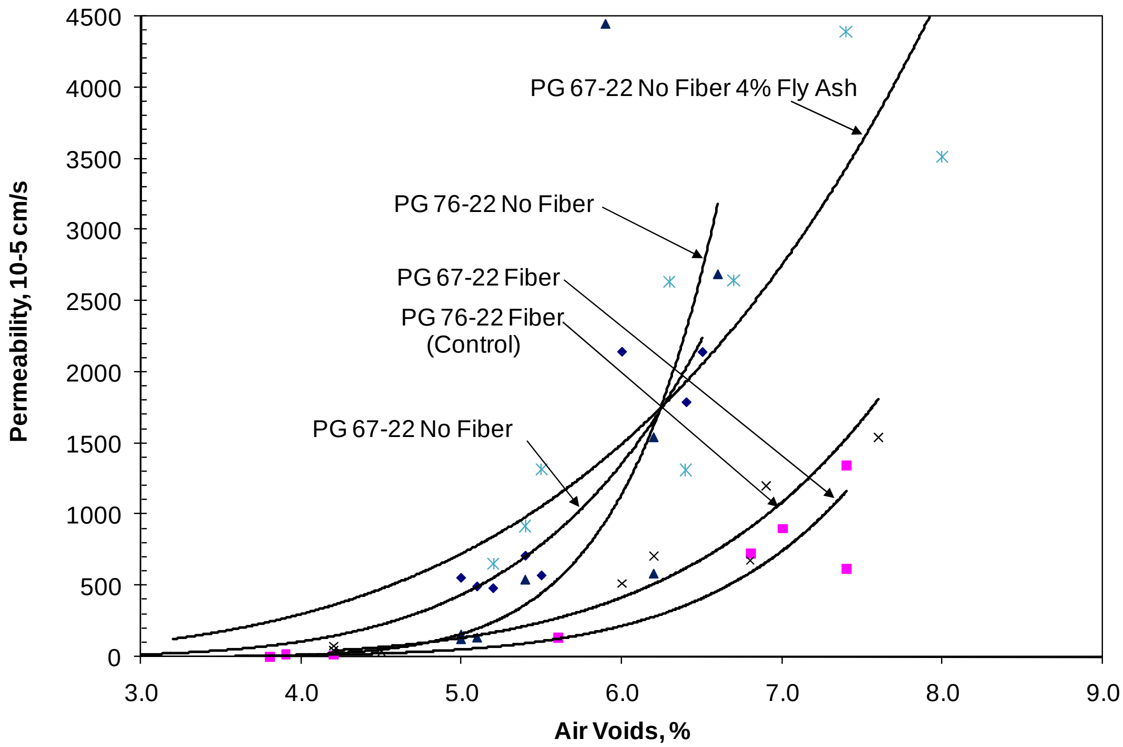

Figure 5. Permeability as a Function of Air Voids

Table 5. Permeability for Various Density Levels

Mix	Permeability		Density for 125 x 10-5 cm/sec
	93% Gmm	94% Gmm	
76-22 Fiber	1102	365	94.9
67-22 Fiber	719	164	94.2
76-22 No Fiber	7051	1086	94.9
67-22 No Fiber	3929	1332	96.0
67-22 No Fiber, 4% Fly Ash	2662	1450	97.2

Generally, the mixes with fibers appear to be less permeable than the mixes without fibers. All of the mixes are permeable at typically specified density levels. For the PG 67-22 mix with no fibers and 4 percent fly ash, there were no tests at lower air void contents. This may have skewed the regression, resulting in higher permeability for a given density level. Since the PG 67-22 mix with 4 percent fly ash has a higher percentage passing the 4.75 mm sieve (No. 4), it might be expected that it would be less permeable.

Specification Development

The preceding results were forwarded to the Alabama Department of Transportation. A draft specification was developed for stone skeleton asphalt with input from the researchers. The draft specification was used to construct trial sections, described in a separate report. The design gradation range is shown in Table 6. The design volumetric properties are summarized in Table 7. PG 67-22 binder was specified. Fiber was required for the design, with the option to reduce or eliminate during field production. Up to 15 percent reclaimed asphalt pavement (RAP) was allowed in the mix. The minimum asphalt content is the same as that specified for SMA mixes. The maximum APA rut depth was increased from 4.5 mm in consideration of the use of PG 67-22.

Table 6. Design Gradation Range

Sieve Size	3/4 inch (19.0 mm) NMAS	
	Lower Limit	Upper Limit
1 inch (25.0 mm)	100	100
3/4 inch (19.0 mm)	90	100
1/2 inch (12.5 mm)	50	74
3/8 inch (9.5 mm)	25	60
# 4 (4.75 mm)	20	28
# 8 (2.36 mm)	15	24
# 16 (1.18 mm)	12	21
# 30 (600 μm)	10	18
# 50 (300 μm)	10	15
# 200 (75 μm)	6	10

Table 7. Design Volumetric Properties

Property	Criteria
N_{design}	65 gyrations
Air Voids	4.0 %
VMA	16.0% minimum
Asphalt Content	5.5% minimum
VCA_{Mix}	$< VCA_{DRC}$
APA Rut Depth at 67C	5.75 mm or less

Cost Implications

The use of polymer modified binder, fibers, and mineral filler in SMA all increase cost over conventional dense-graded HMA. Cost savings could also be obtained from reduced asphalt content if fibers are not specified. Polymer modified PG 76-22 reportedly costs about 32 percent more than neat PG 64 or 67-22. The addition of fibers and mineral filler results in cost increases for the additive itself as well as the equipment needed to introduce it.

In the case of a fiber feeder, it can be purchased or leased; however, a mineral filler silo would be purchased. Some contractors have been successful introducing mineral filler through their existing cold-feed bins. Others may already have a mineral filler silo. In either of these cases there would not be an additional equipment cost for the introduction of the mineral filler.

When a contractor purchases equipment, they expect a return on their investment. The Federal government allows capital recovery through depreciation, over a seven-year period. In addition, the contractor would most likely include some level of profit in their overhead based on this investment. In many cases, the scenario is somewhat different for specialty equipment required to produce a specific mix for a specific job or jobs. A fiber feeder probably falls into this category. A mineral filler silo may be more readily resold or salvaged.

Ideally, the contractor may like to recoup this investment on that particular job. That may be possible with a work order; however, for a low bid project, this will probably need to be spread out over three to four years in order for the contractor to actually get the job. A three-year amortization period was selected for this example. If the contractor had not purchased a particular piece of equipment, they could have simply invested that money and would expect a return on their investment. The same holds true for the equipment, a contractor would hope to get more than their money back at the end of the three-year period. Twelve percent compounded interest was selected as a rate of return for this example. It was assumed that 15,000 tons of SMA would be produced in each of the three years of the amortization period. The cost of a 750 barrel mineral filler silo was used in the calculations. Fiber feeders can be leased. For the tonnage produced, it was deemed cheaper to lease. The lease cost includes, freight, set up, and training.

Table 8 shows the cost saving potential from eliminating various components of SMA while still producing a stone skeleton mix. Costs for equipment purchase, lease, and for the materials themselves were obtained from representative manufacturers and suppliers. They are an estimate for a single point in time (Spring 2008) and subject to change.

Table 8. Cost Impacts for Components of SMA

Item	Description	Equipment cost/ton	Material cost/ton	Total cost/ton
Polymer modification	5.5% Optimum	NA	$6.04	$6.04
	5.0% Optimum	NA	$5.50	$5.50
Mineral filler	2%	$4.37	$0.67	$5.04
	4%	$4.37	$1.34	$5.71
Fiber	0.3%	$0.63	$1.08[1]	$1.71
0.5% Increase in binder content due to fiber addition	PG 76-22	NA	$2.31	$2.31
	PG 64-22	NA	$1.75	$1.75

[1]Frieght costs were not available for the fiber. Freight may cost as much as the fiber itself.

Polymer modification has the highest cost. Polymer modification may be used to reduce rutting potential, to improve durability or both. Polymer modification was still a significant factor in the rutting potential of the stone skeleton mixes, although the addition of 2 percent additional fly ash (which resulted in a reduction in VMA and optimum asphalt content) performed similarly. Durability was not assessed in this study. The larger mastic film thickness of stone skeleton mixes should improve durability. A comparison of companion sections from in-service pavements estimates that polymer modified binders result in a 25 percent or 2 to 10 year increase in service life (*7*).

The cost of a mineral filler silo adds significantly to the cost of mineral filler addition. As noted previously, some contractors may already have a mineral filler silo or may choose to use a cold feed bin to introduce mineral filler in a stone skeleton mix. Although the cost of fiber addition appears to be less, when coupled with the resulting increase in VMA and optimum asphalt content, the total cost is between $3.46 and $4.02 per ton, without freight charges for the fiber. Fiber reduced draindown, permeability (at higher air voids), and rutting potential with the PG 67-22 binder.

Additional research and field trial sections would be necessary to investigate the affect on long-term durability of the various components. This would provide data for a life-cycle cost analysis, which could be used to identify the most beneficial components.

CONCLUSIONS

A study was conducted to evaluate the concept of stone skeleton asphalt. The concept was to produce a mixture with performance properties close to SMA, but at a reduced cost. The use of polymer modified binder, fibers and mineral filler, as well as its higher asphalt content, increase the cost of SMA mixtures as compared to dense graded mixtures. These components were systematically removed and the performance evaluated in terms of draindown, rutting potential, and permeability. The following conclusions can be drawn from the data:

- The inclusion of fibers increases both the VMA of the mixture and its design asphalt content.
- As expected, the inclusion of fiber significantly reduces draindown. However, the mixes without fiber did not exceed the recommended maximum laboratory draindown.

Additional fly ash did not appear to reduce the draindown potential. Other mineral fillers may perform differently.

- The rutting potential of the stone skeleton mixtures was not significantly affected by binder content. Although binder grade was a significant factor in the measured rut depth, the inclusion of fibers and particularly additional filler in the mixes containing PG 67-22 resulted in measured rut depths at optimum asphalt content which were not significantly different than those from mixes containing PG 76-22.
- The stone skeleton mixes evaluated in this study were permeable at typically specified in-place densities. The in-place pavement density would need to be approximately 95 percent of maximum theoretical density to produce an impermeable pavement. Higher density requirements could increase construction costs. The presence of fibers tends to reduce permeability at higher air void contents.

Based on the results of this study a draft specification was developed by the Alabama Department of Transportation to produce a field test section. PG 67-22 was specified instead of the PG 76-22 commonly used in SMA in Alabama. Fibers were included as a safety measure with the option to delete during production.

The potential impact on durability, in terms of cracking resistance and moisture susceptibility, between an SMA and stone skeleton mix was not evaluated in this study. Durability should be evaluated to allow a life-cycle analysis of the potential cost savings of stone skeleton asphalt.

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