Performance of Stone Matrix Asphalt Pavements in Maryland

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Abstract

The Maryland State Highway Administration (MSHA) has constructed over 85 Stone Matrix Asphalt (SMA) projects totaling over 1300 lane miles since 1992. The SMA mixes have been placed exclusively on high volume, high speed highway segments. Analyses of nearly 1000 sets of construction quality control test data and approximately 300 sets of pavement performance measurements for up to 10 years of service life conclusively demonstrate the superior performance of SMA mixes in Maryland. Cumulative total rut depth for Maryland SMA projects averaged 0.14 inches for 12.5 mm mixes and 0.13 inches for 19 mm projects. Cumulative IRI values averaged 75.7 inches/mile for 12.5 mm mixes and 97.1 inches/mile for 19 mm projects. Average friction numbers at the last survey were 49.1 for 12.5 mm mixes and 46.5 for 19 mm projects. Mean annual changes in measured performance were less than 0.035 inches/year for rut depth, 1.8 inches/mile-year for IRI, and 1.3/year for friction number. Statistical analyses of Maryland SMA mix volumetric and gradation properties and pavement performance confirm that the Maryland SMA mixes have been well controlled with uniformly excellent performance.

Key Words: Stone matrix asphalt; pavement performance; rutting; roughness; friction

Introduction

Stone Matrix Asphalt (SMA) is a gap-graded hot mix asphalt concrete that combines high quality coarse aggregate with a rich proportion of asphalt cement. This blend produces a stable paving mixture with a strong stone-on-stone skeleton that provides outstanding rutting resistance and durability.

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Originally developed by German contractors, SMA has achieved considerable prominence over the past 25 years in northern and central Europe. Based on this European experience, the Maryland State Highway Administration began to specify SMA on major high traffic, high speed arterial roads in 1992. Initial Maryland efforts attempted to duplicate as nearly as possible the European technology for design, production and placement of SMA. These procedures evolved as MSHA acquired local experience with this new material. The current Maryland SMA design specification is very similar to the recommendations of the Federal Highway Administration SMA Technical Working Group. SMA mixtures in Maryland have been produced in both drum and batch plants using a variety of aggregates, binders, modifiers and stabilizers.

This paper summarizes nearly 1000 sets of construction quality control test data and approximately 300 sets of pavement performance measurements for up to 10 years of service life. Analyses of these data quantitatively and conclusively demonstrate the superior performance of SMA mixes in Maryland, with very little rutting, increased roughness, or decreased friction observed even after 10 years of service life. Secondary benefits include reduced tire splash and reduced tire noise.

SMA has proven itself in Maryland to be a premium paving material for demanding applications. Nationally, SMA mixtures typically cost 20 to 50 percent more than conventional dense-graded asphalt mixtures (1); Maryland's experience suggests a somewhat lower cost premium of 10 to 30 percent. In either case, the increase in pavement life from reduced rutting and increased durability is judged to more than outweigh the increased material cost.

Stone Matrix Asphalt

Excellent recent reviews of SMA mixture design, construction methods, and quality control/quality assurance (QC/QA) procedures are given by Brown and Cooley (2) and by Hughes (1). In addition, Michael (3) summarizes Maryland's early experiences with SMA design and construction.

SMA Mixture Characteristics

Noteworthy features of SMA mixtures used in Maryland are as follows:

- *Aggregate Quality*. High quality coarse aggregates are required for SMA mixtures. Coarse aggregate should be cubical with 100 percent crushed faces. The coarse aggregate must also be sufficiently hard and durable to minimize particle breakage at the stone-to-stone contacts. Fine aggregate should also be 100 percent crushed. Maryland has ready access to high quality aggregate in most parts of the state, with crushed limestone predominating in the western mountainous regions and crushed limestone diabase in the central part of the state. Imported aggregate is require primarily on the Eastern Shore of the Chesapeake Bay and is typically crushed greenstone from Pennsylvania or western Maryland. High skid-resistance imported aggregate is sometimes used in other parts of the state as well. Table 1 summarizes the current Maryland mix design specifications for coarse aggregate quality. Maryland specifications for fine aggregate quality require that the material be 100 percent nonplastic (AASHTO T90) crushed aggregate with a maximum sodium sulfate soundness (AASHTO T104) loss of 12 percent.

Table 1. Current Maryland Specifications for Coarse Aggregate Quality

TEST PROPERTY	TEST METHOD	SPECIFICATION LIMITS
LA Abrasion loss, % max	T 96	30
Flat and Elongated Particles, % retained on No. 4 sieve max	D 4791	
3:1		20
5:1		5
PV	MSMT 411	8.5(d)

- *Gradation*. SMA aggregates are gap-graded to maximize stone-on-stone contact in the aggregate skeleton. Table 2 summarizes the current Maryland mix design specifications for SMA gradations. A 19 mm nominal maximum size has been the most common mixture for early SMA projects in Maryland, largely because it was the most common European mixture at the time of the FHWA-sponsored European study tour in 1990 (Brown and Cooley, 2). More recent Maryland SMA projects have used 12.5 mm mixes, and Maryland has recently begun placing 9.5 mm SMA mixtures as well.

- *Mortar*. SMA mixtures typically have high asphalt cement contents. Asphalt cements are classified using the Superpave Performance Grading system, with the design high temperature grade often increased by one or two grades for SMA mixtures. Nearly all Maryland SMA projects have used unmodified PG 70-22 or modified PG 76-22 binder, depending upon traffic level. Current specifications require elastomeric polymers for modified binders, although other types have been employed in the past. Mineral filler and stabilizing agents (typically cellulose or mineral fibers and/or polymers) are used to provide a satisfactory mortar consistency and to prevent draindown of the binder during transport and paving. Current Maryland mix design specifications for minimum binder content and stabilizers are summarized in Table 3.

Table 2. Current Maryland Specifications for SMA Gradation

Sieve, mm	19 mm NMAS		12.5 mm NMAS		9.5 mm NMAS	
	Lower	Upper	Lower	Upper	Lower	Upper
37.5						
25.0	100	100				
19.0	100	100	100	100		
12.5	82	88	90	99	100	100
9.5		60	70	85	70	90
4.75	20	28	30	50	30	50
2.36	14	20	20	33	20	30
1.18	--	--	--	--	--	--
0.6	--	--	--	--	--	--
0.3	--	--	--	--	--	--
0.15	--	--	--	--	--	--
0.075	9	11	8	11	8	13

NMAS – Normal Maximum Aggregate Size - one sieve size larger than the first that retains more than 10 percent.

- *Laboratory Compaction*. SMA mixtures can be compacted in the laboratory using either a Marshall hammer or the Superpave gyratory compactor. Except for very early projects, all Maryland SMA mixtures have been designed using gyratory compaction. The design asphalt content is selected to produce 4 percent air voids in the compacted mixture. Design asphalt contents for SMA mixes are typically greater than those for conventional DGA mixes and usually exceed 6 percent. VMA values for SMA mixes are also higher, generally exceeding 17 percent. Current Maryland design specifications for Superpave gyratory compacted mixtures are given in Table 3. Maryland also requires a minimum tensile strength ratio (AASHTO T283) of 85 percent for all SMA mixtures.

Table 3. Current Maryland Specifications for SGC Compacted SMA Mixtures

	VMA	VTM	N DESIGN	AC	BINDER
Hot Mix Asphalt 19 mm Gap-Graded	18.0 min.	4.0	100	6.5 min.	PG XX -22
Plant Control	17.0 min.	+ 1.2		+ .4	

	SPECIFICATION	PLANT TOLERANCE
Draindown (test method attached %max	0.3	0.3 max
Stabilizer by weight of total mix %	0.2 - 0.4	+0.1

Maryland Project Experience

Maryland has constructed over 85 Stone Matrix Asphalt (SMA) projects since 1992. The SMA mixes have been placed exclusively on high volume, high speed highway segments where the traffic counts exceed 20,000 AADT and the posted speed is 55 mph or higher.

Project data, construction quality control test data, and pavement performance data are maintained by MSHA in separate standalone databases. As part of a pilot project, these data were all combined into a single Internet-based data storage, reporting, and display system developed by Mahoney and colleagues (4) at the University of Washington. These combined data can be downloaded as Excel spreadsheets for detailed analysis.

A total of 86 contracts spanning 1318 lane-miles of SMA paving are included in the database. Some projects contained more than one SMA mixture. Approximately 80 percent of the SMA lane mileage in Maryland has been on Interstate highways, with the remainder split evenly between U.S. and Maryland state highways. Maryland SMA mixes have included 9.5, 12.5, and 19 mm nominal maximum aggregate sizes, with the 19 mm mixes being the most widely used.

SMA Mixture Characteristics

Aggregates

Maryland SMA mixtures include 9.5, 12.5, and 19 mm nominal maximum aggregate size. The parent rock types for the aggregates include diabase, diorite, gabbro (coarse aggregate only), gneiss, and limestone. Mineral filler is predominantly limestone.

Aggregate specific gravities range between 2.720 to 3.041 for both the coarse and fine aggregates. Absorption range between 0.3 and 1.0 percent; soundness between 0.1 to 1.4 percent. Coarse aggregate LA Abrasion values range between 13 to 22; polish values between 9.8 to 13.3.

Gradation

Mixture gradations were obtained from sieve tests performed as part of the quality control (QC) program. Since only one 9.5 mm project has been constructed to date in Maryland, only gradation data for the 12.5 and 19.0 mm mixes are presented here.

Gradation measurements were available for thirty-four 12.5 mm SMA mixes over 21 projects and twenty-seven 19 mm SMA mixes over 20 projects. Note that more than 60 19 mm SMA projects have been constructed in Maryland since 1992, but QC database information were readily available for only 20 of these (predominantly but not exclusively projects completed since 1996). Table 4 summarizes the minimum, maximum, mean, standard deviation, and coefficient of variation values for the gradation data over the complete sets of Maryland 12.5 and 19 mm SMA mixes.

Note that the individual projects were designed and constructed at different times and under evolving specifications and thus the multi-project statistics in Table 4--especially the minimum and maximum individual measurements and the standard deviation values—will be different from the values for individual projects. In either case, though, the variability is quite low. The standard deviation values are generally less than 2 percentage points for all sizes except 4.75 and 9.5 mm, where the standard deviations increase to about 4 to 10 percentage points.

Table 4. Summary Gradation Data for Maryland SMA Mixes

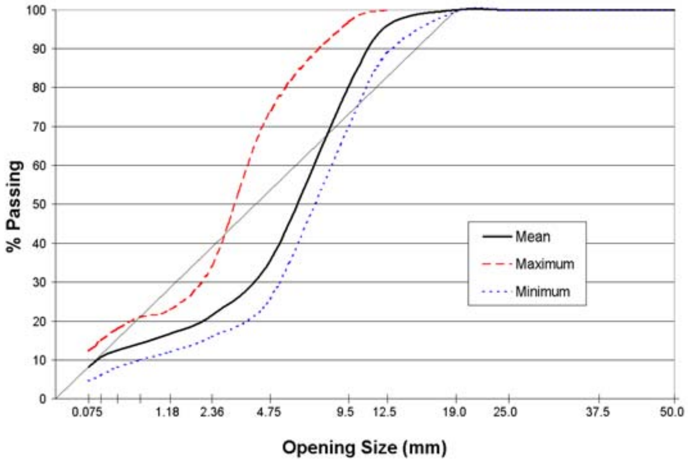
(a) 12.5 mm mixes

	Minimum	Maximum	Mean	Std Dev	COV (%)
% < 0.075 mm	4.6	12	8.2	1.10	13%
% < 0.15 mm	6	15	10.8	1.63	15%
% < 0.30 mm	8	18	12.6	1.73	14%
% < 0.60 mm	10	21	14.2	1.66	12%
% < 1.18 mm	12	23	16.8	1.69	10%
% < 2.36 mm	16	34	21.5	2.25	10%
% < 4.75 mm	26	50	35.5	4.19	12%
% < 9.5 mm	70	97	80.4	3.90	5%
% < 12.5 mm	89	100	96.0	1.44	2%
% < 19.0 mm	100	100	100.0	0.02	0%
% < 25.0 mm	100	100	100.0	0.00	0%

(b) 19 mm mixes

	Minimum	Maximum	Mean	Std Dev	COV (%)
% < 0.075 mm	6.1	11.6	8.5	1.17	14%
% < 0.15 mm	8	16	11.2	1.55	14%
% < 0.30 mm	9	18	12.7	1.72	14%
% < 0.60 mm	10	19	13.8	1.72	12%
% < 1.18 mm	11	21	15.2	1.85	12%
% < 2.36 mm	12	24	18.7	2.01	11%
% < 4.75 mm	20	37	27.4	2.85	10%
% < 9.5 mm	34	90	63.0	9.74	15%
% < 12.5 mm	76	100	84.9	6.37	8%
% < 19.0 mm	97	100	99.9	0.36	0%
% < 25.0 mm	100	100	100.0	0.00	0%

(a) 12.5 mm mixes



(b) 19 mm mixes

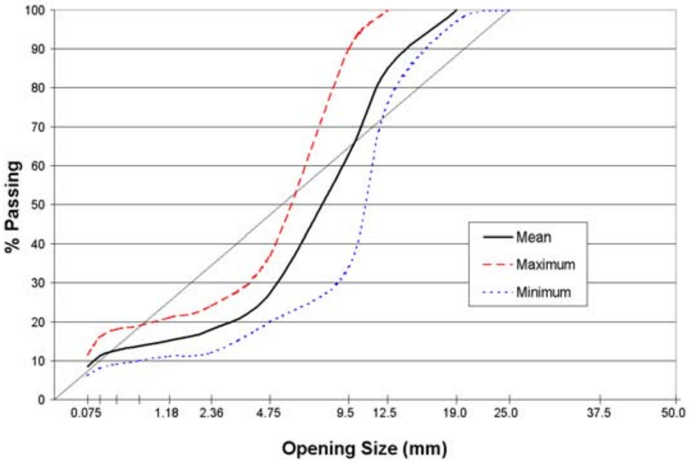


Figure 1. Measured Gradation for Maryland SMA Mixes

The gradation bands for all 12.5 and 19 mm mixes are plotted in Figure 1. Again, the data used to generate these figures are pooled over all projects for a given mix size; any individual project will have a much narrower gradation band. Figure 2 summarizes the frequency distributions for the pooled 19 mm gradation data for selected sieve sizes. The distributions are reasonably normal (i.e.,

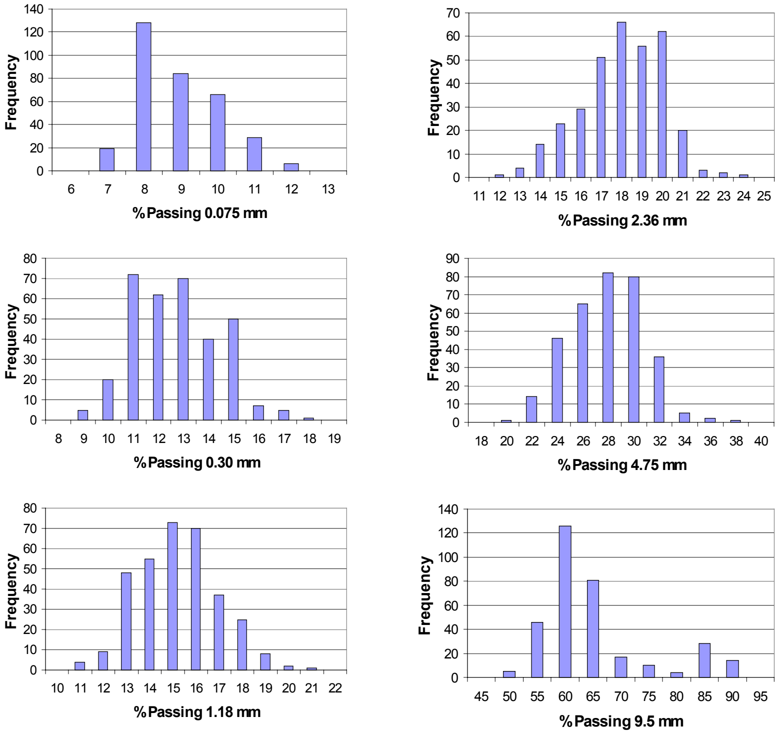


Figure 2. Gradation Distributions at Selected Sieves for Maryland 19 mm SMA Mixes

bell-shaped) with only a few outlier data points (note that not all outliers are necessarily shown in these figures). The largest spread in the distributions occurs in for the 9.5 mm sieve, which is consistent with the data in Table 4. Table 5 compares the mean measured gradation values for the Maryland 12.5 and 19 mm SMA mixes against the Brown and Cooley (2) recommendations and the Maryland specification requirements. Note that most of the Maryland projects were designed and constructed before the Brown and Cooley recommendations were established or published.

Volumetrics

Volumetric properties were obtained from tests performed on laboratory compacted samples as part of the quality control (QC) program. All laboratory specimens were compacted using the

Table 5. Comparison of Gradation Ranges for Maryland SMA Mixes

(a) 12.5 mm mixes

	Measured Mean	Recommended Limits[1]		Maryland Specifications	
		Lower	Upper	Lower	Upper
% < 25.0 mm	100.0				
% < 19.0 mm	100.0	100	100	100	100
% < 12.5 mm	96.0	90	100	90	99
% < 9.5 mm	80.4	26	78	70	85
% < 4.75 mm	35.6	20	28	30	50
% < 2.36 mm	21.5	16	24	20	33
% < 1.18 mm	16.8	13	21	--	--
% < 0.60 mm	14.2	12	18	--	--
% < 0.30 mm	12.6	12	15	--	--
% < 0.15 mm	10.8	--	--	--	--
% < 0.075 mm	8.2	8	10	8	11

(b) 19 mm mixes

	Measured Mean	Recommended Limits[1]		Maryland Specifcations	
		Lower	Upper	Lower	Upper
% < 25.0 mm	100.0	100	100	100	100
% < 19.0 mm	99.9	90	100	100	100
% < 12.5 mm	84.9	50	74	82	88
% < 9.5 mm	63.0	25	60		60
% < 4.75 mm	27.4	20	28	20	28
% < 2.36 mm	18.7	16	24	14	20
% < 1.18 mm	15.2	13	21	--	--
% < 0.60 mm	13.8	12	18	--	--
% < 0.30 mm	12.7	12	15	--	--
% < 0.15 mm	11.2	--	--	--	--
% < 0.075 mm	8.5	8	10	9	11

[1] Brown and Cooley (1999)

Superpave gyratory compactor at N_{Design} = 100 gyrations. Since only one 9.5 mm project has been constructed to date in Maryland, only volumetric data for 12.5 and 19.0 mm mixes are presented here.

Volumetric property measurements were available for thirty-four 12.5 mm SMA mixes over 21 projects and for twenty-seven 19 mm SMA mixes over 20 projects. Note that more than 60 19 mm SMA projects have been constructed in Maryland since 1992, but QC database information were readily available for only 20 of these (predominantly but not exclusively projects completed since 1996). Table 6 summarizes the pooled minimum, maximum, mean,

Table 6. Summary Volumetric Data for Maryland SMA Mixes

(a) 12.5 mm mixes

	Minimum	Maximum	Mean	Std Dev	COV (%)
Asphalt Content (%)	4.1	7.3	6.38	0.222	3%
Air Voids (%)	1.03	7.74	3.61	0.717	20%
VMA (%)	16.0	22.6	18.3	1.18	6%
VFA (%)	65.0	94.0	80.3	3.50	4%
Dust Ratio	0.74	2.37	1.34	0.230	17%
Gmm	2.418	2.642	2.545	0.0588	2%
Gmb	2.241	2.555	2.454	0.0595	2%

(b) 19 mm mixes

	Minimum	Maximum	Mean	Std Dev	COV (%)
Asphalt Content (%)	4.4	6.9	6.38	0.257	4%
Air Voids (%)	1.60	9.70	3.50	1.199	34%
VMA (%)	15.4	24.1	18.8	1.34	7%
VFA (%)	75.0	89.0	81.3	3.61	4%
Dust Ratio	0.98	2.07	1.33	0.194	15%
Gmm	2.385	2.680	2.556	0.0671	3%
Gmb	2.237	3.592	2.466	0.0698	3%

standard deviation, and coefficient of variation values for the volumetric data over the complete set of Maryland 12.5 and 19 mm SMA mixes. Note that the individual projects were designed and constructed at different times and specifications and thus the pooled values in Table 6--and especially the variability data—will be different from project-by-project statistics. Even for the pooled data, however, the variability is quite low. The coefficients of variation are generally less than about 5 to 7 percent except for air voids and dust ratio, where the coefficients of variation increase to near 20 and 35 percent, respectively. Figure 3 summarizes the frequency distributions for the pooled volumetric data for selected properties. The distributions are generally normal (i.e., bell-shaped) with only a few outlier data points (note that not all outliers are necessarily shown in these figures). The broadest distribution is for air voids in Figure 3, which is consistent with the data in Table 6; this distribution is also the most skewed.

Key observations regarding the volumetric properties of the Maryland SMA mixes include the following:

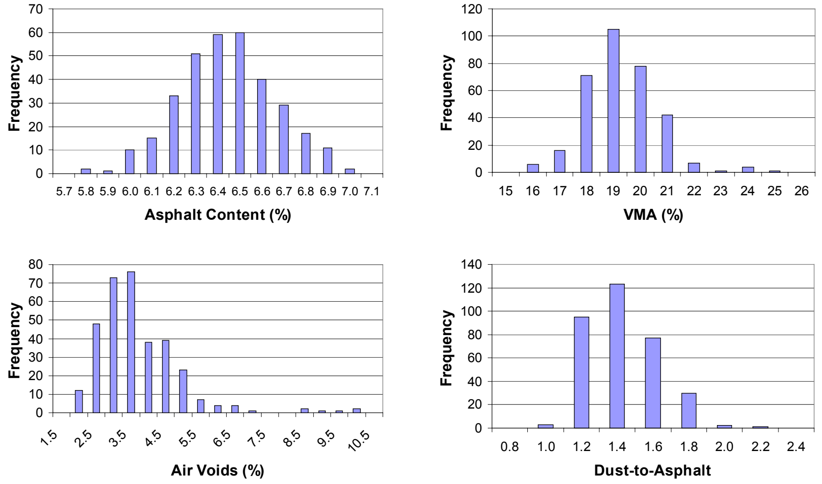


Figure 3. Distributions of Selected Volumetric Properties for Maryland 19mm SMA Mixes

- The average of the mean asphalt contents for these mixes is approximately 6.3 (12.5 mm) to 6.4 percent (19 mm), which is within the Maryland specification tolerances as given in Table 3 and well above the minimum AC recommendations given by Brown and Cooley (2).
- The average of the mean air voids for these mixes is approximately 3.5 (19 mm) to 3.6 percent (12.5 mm), which is within the Maryland specification tolerances as given in Tab;e 3 and slightly below the AV recommendations given by Brown and Cooley (2).
- The average of the mean VMA values for these mixes was 18.6 (12.5 mm) and 18.8 percent (19 mm), which satisfies the Maryland specification limit as given in Table 3 and is consistent with the recommendations given by Brown and Cooley (2).
- There is very little variability in the G_{mm} and G_{mb} specific gravity measurements.

Note that many of these mixes were designed and constructed before the Brown and Cooley guidelines were formalized and published.

Performance

Performance data for the SMA projects was extracted from the Maryland Pavement Management System and combined with the QC data. Performance measures included rut depth, roughness as quantified by the International Roughness Index (IRI), and skid resistance as quantified by the Friction Number (FN). No visual survey data were included. A total of 324 records (38 for 12.5 mm mixes, 286 for 19 mm mixes) of performance data were included in the database.

The time values for all data points are computed as the elapsed time since the end of construction to the time of performance measurement. The end of construction date was specified by month and year in the performance database. The time of performance measurement was specified by year only, however, so for the purposes of computing elapsed time it was assumed that all performance measurements were made in July of the measurement year. Computed performance periods ranged up to 10 years of pavement service for some projects.

Performance Trends

Plots of rut depth, roughness (IRI), and friction (FN) versus time are presented in Figures 4 through 6, respectively. Data for both 12.5 mm and 19 mm projects are combined on the graphs, with most of the data corresponding to 19 mm mixes. Only one 9.5 mm project was included in the Maryland SMA database; this project is not included in the figures.

The overall conclusion from the trends shown in these figures is that the performance of the SMA mixes has been excellent. Values for rutting, IRI, and friction are all very good, even after 10 years of service life.

The trends for rut depth vs. time (Figure 4) are consistent for both the 12.5 mm and 19 mm mixes. Both mix sizes show very slight increases in rutting with time; the small slope coefficients and low R^2 values for the trend lines indicate that the rut depth vs. time trend is essentially flat (recall that the R^2 value for a horizontal regression line is zero by definition).

The trends for IRI vs. time (Figure 5) are slightly inconsistent for the 12.5 and 19 mm mixes. The 19 mm data show a slight increase in roughness with time, as would be expected intuitively, while the 12.5 mm data show a counterintuitive slight decrease with time. In both cases, however, the changes in roughness over

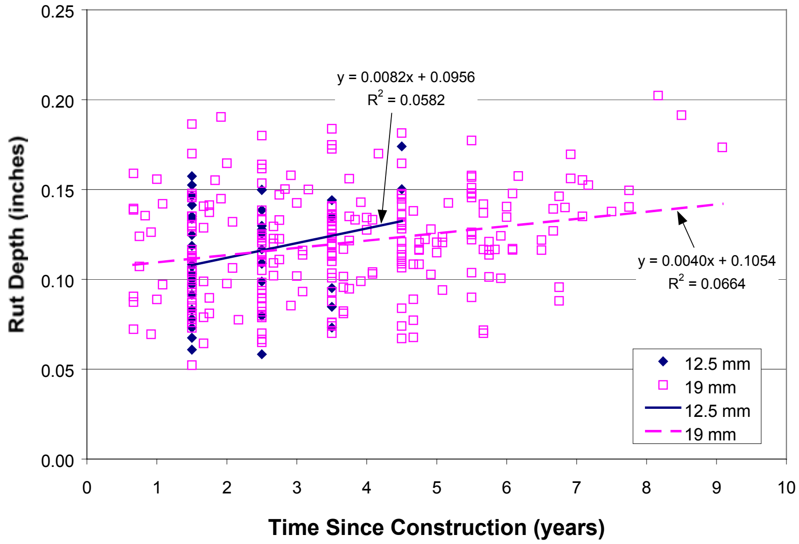


Figure 4. Rut Depth vs. Time for Maryland SMA Projects

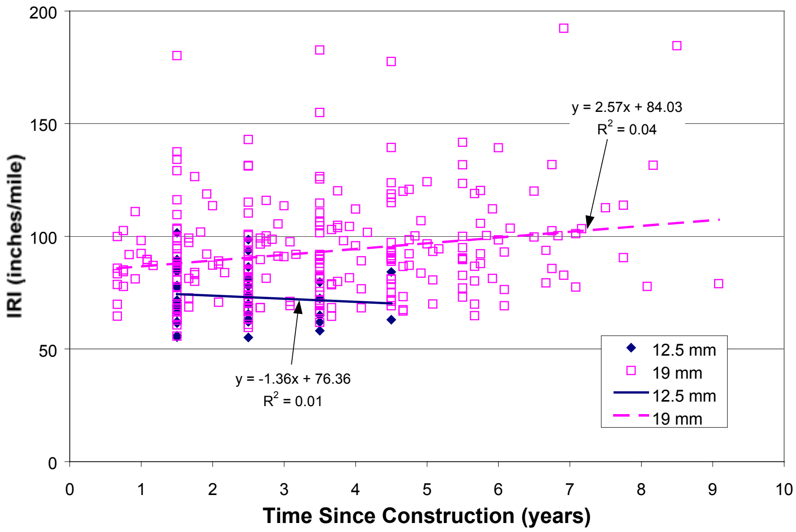


Figure 5. IRI vs. Time for Maryland SMA Projects

time are very small, as indicated by the small slope coefficients and the correspondingly low R^2 values of the trend lines, and the apparent discrepancy in the trends of IRI vs. time for the two mix sizes is insignificant in practical terms.

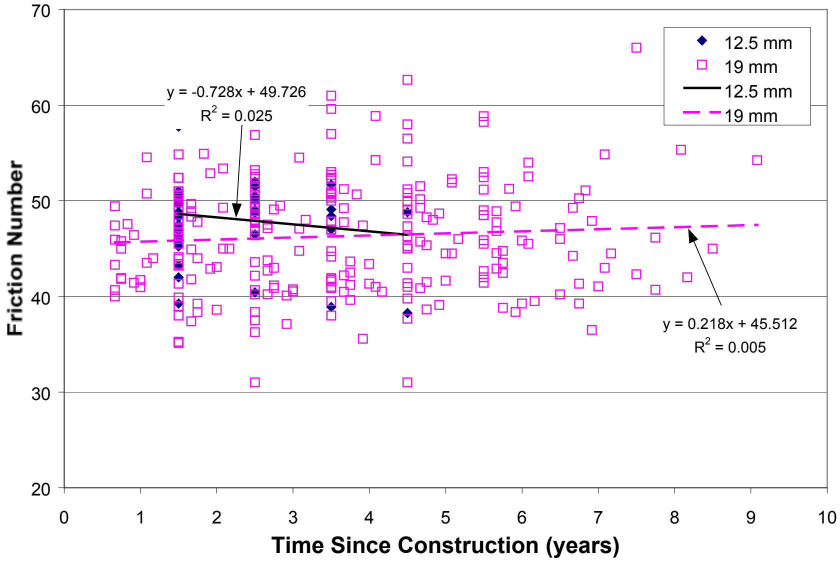


Figure 6. Friction vs. Time for Maryland SMA Projects

The trends for friction vs. time (Figure 6) are also slightly inconsistent for the two mix sizes, with the 12.5 mm data showing a slight decrease and the 19 mm data showing a slight increase in friction over time. As in the case of the IRI data, however, the changes in friction are very small (note the small slope coefficients and low R^2 values in the trend lines), and the discrepancies in the trends of friction vs. time for the two mix sizes is insignificant in practical terms.

Figure 7 summarizes the distributions of measured rut depth, IRI, and FN for all of the measurements in the performance database. Direct comparison of all of the data in the performance database is not completely consistent, since the projects have different ages at each survey year. However, as shown previously in Figures 4 through 6, the variation of the performance measures over time are all relatively small, and the frequency distributions in Figure 7 can provide a quantitative feel for the ranges and variability of the pavement performance. Note that the number of 19 mm projects is much larger than the number of 12.5 mm projects, and the frequency distributions have therefore been normalized in percentage terms.

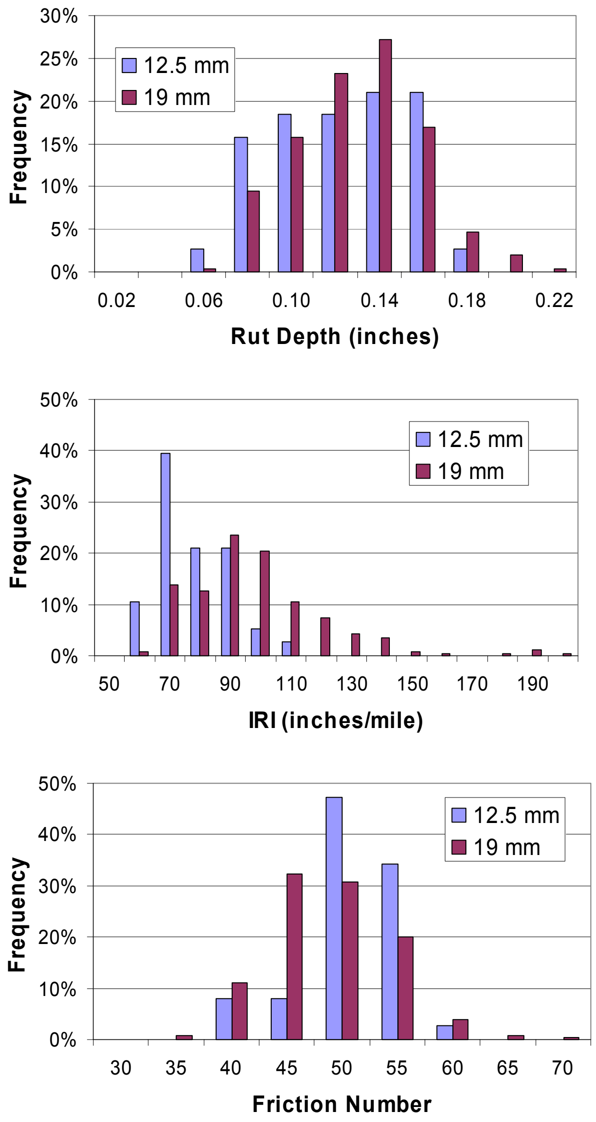


Figure 7. Distributions of Cumulative Performance Measures

As shown in Figure 7, values for cumulative total rut depth at the latest survey date averaged 0.14 inches (range=0.10-0.17, σ=0.021) for the 12.5 mm mixes and 0.13 inches (range=0.00-0.20, σ=0.046) for the 19 mm projects. Values for cumulative IRI at the latest survey date averaged 75.7 inches/mile (range=61.9-

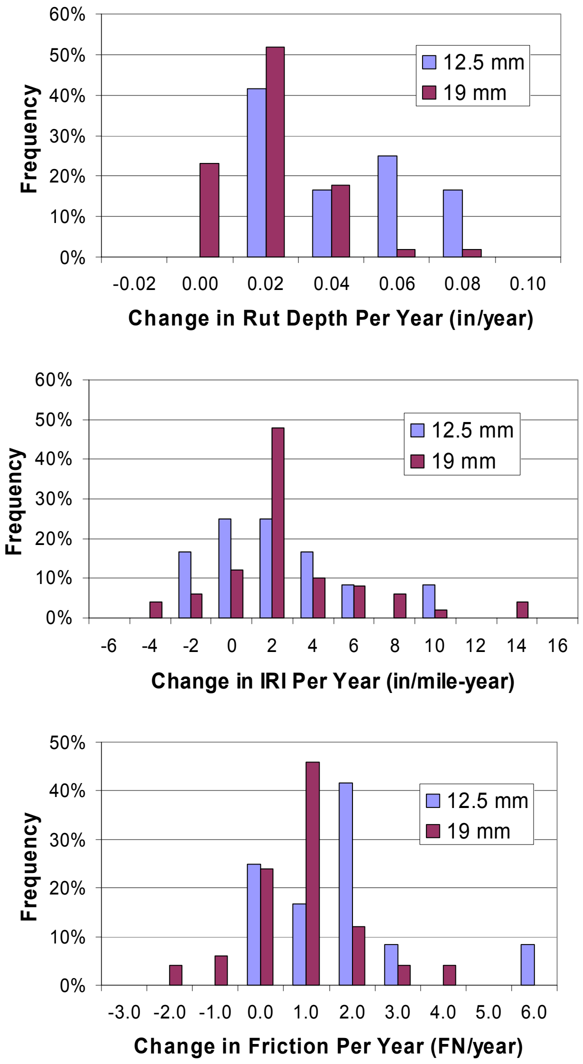


Figure 8. Distributions of Annual Changes of Performance Measures

98.5, σ=12.6) for the 12.5 mm mixes and 97.1 inches/mile (range=59.5-192.3, σ=30.0) for the 19 mm projects. Values for FN at the latest survey date averaged 49.1 (range=38.3-52.0, σ=3.9) for the 12.5 mm mixes and 46.5 (range=31.0-58.9, σ=5.3) for the 19 mm projects.

A more useful evaluation of the performance of the SMA projects is in terms of the average *changes* in performance measures per year. The average annual changes are determined as the difference between the last and first available survey data divided by the number of years between surveys. This methodology implies that only projects having at least two performance surveys can be included in the data set. A major advantage of this approach, however, is that it removes the variability in absolute performance values attributable to differences in initial (post-construction) performance measurements.

Frequency distributions for the annual changes in rut depth, roughness, and skid resistance are presented in Figure 8. As indicated in these figures, the mean magnitudes of the annual changes in performance are quite small. This is better illustrated by the summary statistics for the annual changes in performance in Table 7: the mean annual changes are less than 0.04 inches/year for rut depth, 3.2 inches/mile-year for IRI, and 1.3/year for FN. These mean values for the annual performance changes are so small that they can be taken as zero in practical terms. Note, however, that the variability of the annual performance changes is quite high; the coefficients of variation are often on the order of hundreds of percent.

Correlations Between Performance and Mixture Properties

A final analysis was performed to investigate correlations between performance data and volumetric and gradation data for the Maryland SMA projects. Given the consistently excellent performance of the SMA pavements and the relatively small variation of volumetric and gradation properties within each mix type, it was doubtful from the start whether this exercise would provide any meaningful insights. As will be seen below, the results confirm this expectation.

The sources of data for this correlation study was again the combined QC and performance database compiled by the University of Washington in their web database application. Since this database did not include QC data for projects constructed prior to 1996, additional QC data from Michael (3) was manually entered into the analysis.

One complication is that the Maryland performance data is compiled by project while the QC data are compiled by mix

Table 7. Summary Statistics for Annual Changes in Performance

ΔRutting/Year (inches/year)						
Mix Size	**n**	**Min**	**Max**	**Mean**	**Std Dev**	**COV**
9.5 mm	1			0.025		
12.5 mm	12	0.007	0.077	0.034	0.021	62%
19 mm	56	-0.087	0.069	0.008	0.020	250%

ΔIRI/Year (in/mile-year)						
Mix Size	**n**	**Min**	**Max**	**Mean**	**Std Dev**	**COV**
9.5 mm	1			3.2		
12.5 mm	12	-3.0	9.2	1.3	3.4	262%
19 mm	50	-4.4	13.6	1.8	3.6	200%

ΔFriction/Year (FN/year)						
Mix Size	**n**	**Min**	**Max**	**Mean**	**Std Dev**	**COV**
9.5 mm	1			0.4		
12.5 mm	12	-0.3	5.3	1.3	1.5	114%
19 mm	56	-2.7	3.4	0.3	1.1	335%

design. Several projects have more than one mix design (although always of a single nominal maximum aggregate size). For the purposes of this correlation study, the volumetric properties for multiple mixes in a single project were simply averaged.

The correlations examined in this study are between average *changes* in performance per year and volumetric and gradation properties on a project-by-project basis. Use of annual changes in performance eliminates the confounding effects of different initial values (e.g., different initial IRI values post-construction) in the comparisons. Performance measures in this study were the average annual changes in rut depth, roughness as characterized by IRI, and skid resistance as characterized by Friction Number. Volumetric and gradation properties in this study consisted of the asphalt content (AC), air voids (AV), VMA, and percent passing the 4.75 and 0.075 mm sieves. Only the 12.5 mm and 19 mm projects were considered, and each mix size was analyzed separately.

Correlation matrices for the study variables for the 12.5 and 19 mm projects are given in Table 8. For the purposes of this study,

Table 8. Correlation Matrices

(a) 12.5 mm mixes

	AC	*AV*	*VMA*	*0.075 mm*	*4.75 mm*	*Δ IRI/Year*	*Δ Rutting/Year*	*Δ Friction/Year*
AC	1.00							
AV	0.29	1.00						
VMA	0.24	0.29	1.00					
0.075 mm	0.06	0.18	-0.32	1.00				
4.75 mm	0.10	-0.05	0.12	-0.31	1.00			
Δ IRI/Year	**-0.29**	-0.09	**0.24**	**-0.19**	-0.09	1.00		
Δ Rutting/Year	**-0.23**	**-0.22**	**-0.17**	-0.04	**-0.52**	0.51	1.00	
Δ Friction/Year	**-0.42**	**-0.47**	**-0.32**	-0.08	**-0.47**	-0.12	0.14	1.00

(b) 19 mm mixes

	AC	*AV*	*VMA*	*0.075 mm*	*4.75 mm*	*Δ IRI/Year*	*Δ Rutting/Year*	*Δ Friction/Year*
AC	1.00							
AV	-0.01	1.00						
VMA	0.25	0.63	1.00					
0.075 mm	0.10	0.28	0.15	1.00				
4.75 mm	-0.15	0.20	0.27	-0.09	1.00			
Δ IRI/Year	**-0.12**	-0.06	0.04	0.05	0.08	1.00		
Δ Rutting/Year	**0.20**	**-0.25**	-0.01	-0.06	**-0.18**	0.09	1.00	
Δ Friction/Year	-0.01	-0.04	0.11	**-0.40**	**0.26**	-0.30	0.20	1.00

the row/column combinations relating performance (last three rows) to QC data (first five columns) are of most interest.

As shown in the Table 8, the correlation coefficients are all very small. The largest correlation coefficients relating performance (last three rows) to QC parameters (first five columns) are indicated in bold font in the tables, but even most of these are below 0.3. Observations drawn from Table 8 include the following:

- ΔRutting/year is negatively correlated with AC, VMA, and percent passing 4.75mm for the 12.5mm projects. Change in rutting for the 19 mm projects is similarly correlated with VMA and percent passing 4.75mm but is positively correlated with AC.
- ΔIRI/year is negatively correlated with AC and percent passing 0.075mm, and positively correlated with VMA for the 12.5 mm projects. Change in roughness for the 19 mm projects is similarly correlated with AC, but the correlations with VMA and 0.075mm are insignificantly small.
- ΔFriction/year is negatively correlated with AC, AV, VMA, and percent passing 4.75mm for the 12.5mm projects. The 19mm projects show no correlation between annual friction change and volumetrics but *positive* correlation with percent

Figure 9. Annual Rut Depth Change vs. AC Content

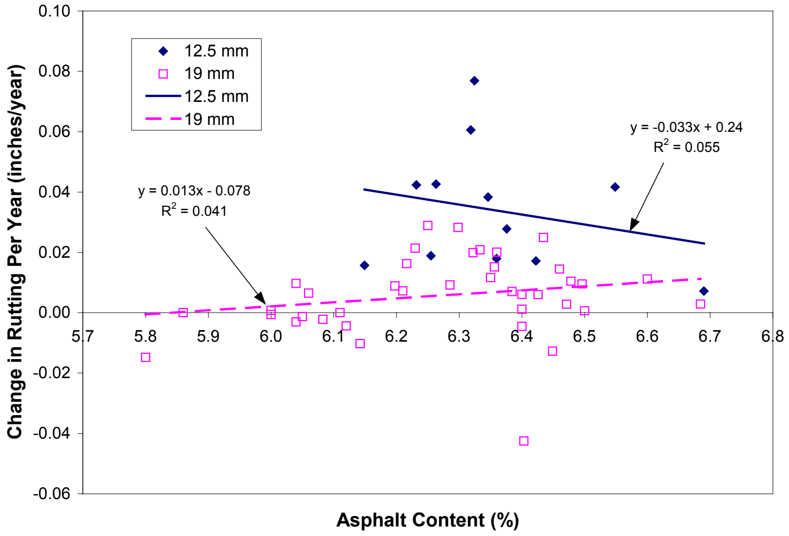
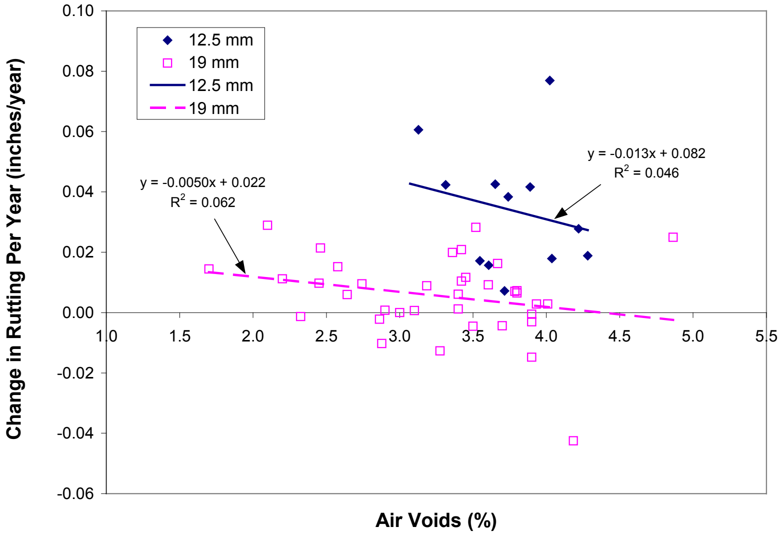


Figure 10. Annual Rut Depth Change vs. Air Voids



passing 4.75mm and negative correlation with percent passing 0.075mm. One would not necessarily expect friction to be correlated with volumetrics for a given nominal maximum aggregate size, except perhaps with AC.

Figure 11. Annual Rut Depth Change vs. 4.75mm Gradation

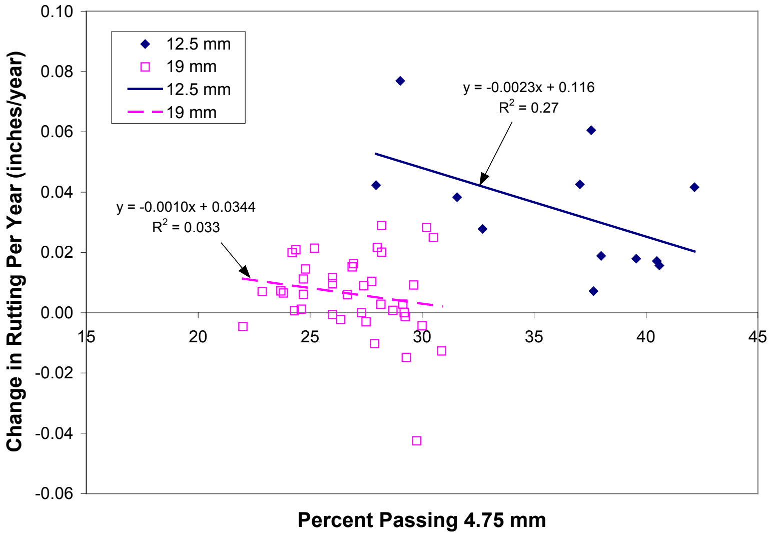
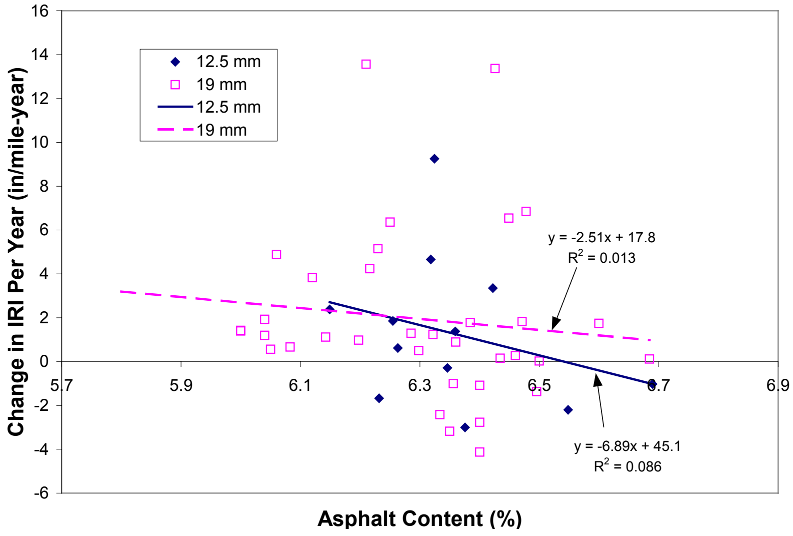


Figure 12. Annular Roughness Change vs. AC Content



Other interesting observations include a modest positive correlation among AC, AV, and VMA, which is expected given the interrelationships among the volumetric properties. There are conflicting correlations between VMA and percent passing

0.075mm; the correlation is moderately negative for 12.5mm projects and slightly positive for the 19mm projects); small to moderate correlation between VMA and 4.75mm. There is a relatively strong positive correlation (as would be expected) between rutting and roughness for the 12.5mm projects, but no correlation for 19mm cases.

Based on all of the above discussion and physical reasoning, the most plausible correlations are between: ΔRutting/year and AC, AV, and percent passing 4.75mm; ΔIRI/year and AC; and ΔFriction/year and percents passing 0.075mm and 4.75mm. Figures 9 through 12 depict the correlations graphically for ΔRutting/year and ΔIRI/year. Although these figures largely reinforce the observations from the correlation matrices, there are some other noteworthy features:

- Figure 9 shows inconsistent and weak trends between annual change in rutting and AC. Correlations between rutting and AV (Figure 10) and percent passing 4.75mm (Figure 11) are more consistent but with different relationships for the 12.5 and 19mm mixes. The correlation between rutting and air voids is a bit counterintuitive in that it shows better performance (less rutting increase per year) as AV increases. The correlation between rutting and percent passing 4.75mm is also a bit counterintuitive for an SMA in that an increase in percent passing 4.75mm correlates with an increase in rutting performance (smaller delta rutting per year).
- Figure 12 shows consistent but weak trends of increasing roughness performance (smaller delta IRI per year) with increasing AC for both mixes, with very similar relationships for the two mix sizes.

The best overall conclusion from this statistical study is that the correlations between Maryland SMA mix volumetric and gradation properties and pavement performance are inconclusive. This should not, however be interpreted as implying that volumetric and gradation properties are unimportant for SMA performance. Rather, the volumetric and gradation properties for the Maryland SMA mixes have been so well controlled and the performance of the Maryland SMA projects has been so uniformly excellent that there simply is too little variation in either to define useful, robust correlations.

Summary

Stone Matrix Asphalt (SMA) is a gap-graded hot mix asphalt concrete that combines a large portion of high quality coarse aggregate and a high content of asphalt cement. This blend produces a stable paving mixture with a strong stone-on-stone skeleton that provides outstanding rutting resistance and durability. SMA is a premium paving material that is best suited for demanding applications.

Maryland has constructed over 85 Stone Matrix Asphalt (SMA) projects since 1992, totaling over 1300 lane miles of paving. The SMA mixes have been placed exclusively on high volume, high speed highway segments where the traffic counts exceed 20,000 AADT and the posted speed is 55 MPH or higher; the vast majority of the SMA placement in Maryland has been on Interstate highways. Maryland SMA mixes have included 9.5, 12.5, and 19 mm nominal maximum aggregate sizes, with the 19 mm mixes being the most widely used

This paper documents the performance of SMA in Maryland. Project data, construction quality control (QC) test data, and pavement performance data maintained in separate standalone databases by the Maryland State Highway Administration were all combined into a single Web-based data storage, reporting, and display system developed at the University of Washington. Nearly 1000 sets of QC properties and over 300 sets of performance measurements were downloaded from this database for detailed statistical analysis. This one of the largest and most accessible sets of SMA project data available to date.

Values for cumulative rut depth for Maryland SMA projects, including projects with up to 10 years of performance data, averaged 0.14 inches for the 12.5 mm mixes and 0.13 inches for the 19 mm projects. Cumulative IRI values at the latest survey date averaged 75.7 inches/mile for the 12.5 mm mixes and 97.1 inches/mile for the 19 mm projects. Values for friction number at the latest survey date averaged 49.1 for the 12.5 mm mixes and 46.5 for the 19 mm projects. Mean annual changes in measured performance are less than 0.04 inches/year for rut depth, 3.2 inches/mile-year for IRI, and 1.3/year for friction. These values for annual performance changes are so small that they can be taken as zero in practical terms.

Analyses of the correlations between Maryland SMA mix volumetric and gradation properties and pavement performance were inconclusive. This should not, however, be interpreted as implying that volumetric and gradation properties are unimportant for SMA performance. Rather, the volumetric and gradation properties for the Maryland SMA mixes have been so well controlled and the performance of the Maryland SMA projects has been so uniformly excellent that there simply is too little variation in either to define useful, robust correlations

In summary, the performance of SMA pavements in Maryland has been outstanding. Very little rutting, increase in roughness, or decrease of friction has been observed, even for pavements that have been in service for as long as ten years. Other notable benefits of SMA include reduced tire splash and reduced tire noise. Many of the Maryland SMA pavement sections look better today than when first opened to traffic.

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