FINAL REPORT

A PERFORMANCE BASELINE FOR STONE MATRIX ASPHALT

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ABSTRACT

In 2003, Virginia launched an expanded commitment to stone matrix asphalt (SMA). By the end of 2004, contracts that encompassed nearly 400,000 tons of SMA had been awarded and most of the material produced and placed. During this 2-year timeframe, more construction districts and contractors were engaged in the design, production, and placement of SMA than at any time in the history of the Virginia Department of Transportation (VDOT). Most were experiencing it for the first time.

This report documents many aspects of the 2003/2004 SMA "implementation initiative." It summarizes and presents detailed information on costs and quantities, volumetric properties, compaction, permeability, aggregate quality, and initial functional character (ride and friction) for SMA pavements placed during the 2003 and 2004 seasons.

SMA is a complex and expensive HMA material. Carefully documenting (or "baselining") today's experiences and understanding the consequences in terms of lifetime costing are important keys to the continued successful deployment of the best HMA technologies for Virginia. If the cost savings associated with SMA (as identified by the National Asphalt Pavement Association) continue and are applied to only the 14% of VDOT's annual program allotted to SMA in 2005, the fruits of this research can contribute to more than $14 million per year in savings.

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INTRODUCTION

An Expanded Deployment of Stone Matrix Asphalt

Stone matrix asphalt (SMA) represents an "Americanized" version of German asphalt technologies. Fundamentally, an SMA paving mixture relies on a stone-on-stone aggregate structure made up of high-quality cubicle aggregates in a rich mixture of premium binding materials. Since the early 1990s in the United States, SMA has demonstrated great promise as a hardwearing, durable mix. In service, it offers the further advantage of gap grading, which generally provides functional improvements over dense-graded mixes.

Since the mid-1990s, the top flexible pavement priority of the Virginia Department of Transportation (VDOT) has been adaptation and implementation of the Superpave® mix design and analysis system for conventional asphalt mixes. Although the success of this program has been outstanding, statewide advancement of SMA technologies has been sluggish to non-existent in the meantime. Now that Superpave has been widely adopted, Virginia is renewing an emphasis on the deployment of SMA.

In 2003, Virginia awarded contracts for SMA in seven of the nine VDOT construction districts. In 2004, six of the districts were involved with SMA, and the total awarded quantities had risen from 180,000 tons in 2003 to 210,000 tons. More districts and contractors were engaged in the design, production, and placement of SMA than at any time in VDOT's history. At the beginning of this period, most were experiencing it for the first time.

Specifications

The 2003 and 2004 timeframe involved two special provisions for SMA design, production, and placement. The first special provision was dated August 25, 1999, and was a mature version of the initial special provision written to switch SMA design and acceptance testing from the Marshall mix design system to a system that incorporated the design procedures of the Superpave system. The second special provision came together in late 2002. It included a finer surface mix and several more subtle changes. Both provisions were applied somewhat during the 2003 construction season. The 2004 work, however, was exclusively from the 2002 provision. Table 1 and the discussion that follows present and contrast a few of the more important criteria provided in the two special provisions. The table also provides the corresponding criteria for the preceding "Marshall SMA" (Clark et al., 2004).

Table 1. SMA Special Provision Summary

Mix Parameter	Marshall	1999	2002
Binder content (min.) • Surface • Intermediate	 6.0 5.5	 6.0 5.5	 6.5[a] 5.5
Compaction (lab)	50 blows (Marshall hammer)	100 gyrations (gyratory compactor)	100 gyrations (gyratory compactor)
Design void target	4.0 (Before 1995) 3.5	3.5	3.5
Production void range	2.5-5.5 (Before 1995) 2.5-4.5	2.5-4.5	2.5-4.5[b] (Surface) 2.0-4.0 (Intermediate)
Voids mineral aggregate (min.) • Surface • Intermediate	 17.0 -	 17.0 16.0	 18.0 17.0
Temperature	50ºF	50ºF	50ºF
Density (min.)	94%	94%	94 %
Density test mode Number of tests	Nuclear/core 10/4	Core 4	Core 5
Rolling mode Number Speed	Static 3 rollers 3 mph	Static 3 rollers 3 mph	Vibratory (max. 3 passes) or static 3 rollers 3 mph
Mineral filler (min.)	70% passing No. 200	70% passing No. 200	55% passing No. 200

Note: For an expanded discussion of the history of SMA specification development, see Clark et al. (2004).
[a]Minimum 6.8% for the SMA 9.5 mix.
[b]Design void range.

1999 Special Provision

The 1999 SMA special provision provided for one SMA surface mix and one intermediate mix. The surface mix gradation was based on the German 16.0 mm mix; the intermediate mix was based on the German 19.0 mm mix. The surface mix called for a minimum 6% (by weight) liquid asphalt (AC) content chosen at an air void level of 3.5% at 100 gyrations in the Superpave gyratory compactor. The asphalt binder was either a performance graded (PG) 70-22 or a PG 76-22. Compaction of the mix required a minimum of three rollers. The minimum size (weight) roller required was 10 tons, and all passes were to be in a static (i.e., non-vibratory) mode unless special permission was received from the engineer. Daily density acceptance was based on four core (or saw-cut plug) samples taken by the contractor at random locations specified by the engineer. The average in-place density for a day's production was specified as 94% of the maximum theoretical density of the mix.

2002 Special Provision

The 2002 special provision provided a second, finer gradation surface mix: an SMA 9.5. The 9.5 mm mix corresponds to the gradations of a German 8.0 mm; the 12.5 mm mix is very similar to the German 11.0 mm mix. The minimum AC content was raised to 6.5% for the original SMA surface mix, designated SMA 12.5. The asphalt content of the SMA 9.5 mix was set at 6.8%. The design AC content continued to be selected at an air void level of 3.5% at 100 gyrations. In addition to the original design range for air voids, the 2002 provision provided for a production range at 2.0% to 4.0%. In the 2002 provision, the PG 76-22 binder was required to be polymer modified. A special paragraph at the end of the coarse aggregate subsection was added to define the point of testing and enforcement of coarse aggregate properties. The gradation band on the No. 4 sieve was expanded for the SMA 12.5 surface mix by increasing the maximum percentage passing the No. 4 sieve from 28% to 35%. The minimum amount passing the No. 200 sieve for mineral filler was lowered to 55%. For compaction, the rollers were allowed to operate in the vibratory mode at the lowest amplitude and the highest frequency, but the number of vibratory passes was limited to a maximum of three passes. An additional (fifth) core sample was required for density acceptance, and daily averages of 93.9% or less resulted in at least a 15% disincentive.

PROBLEM STATEMENT

In comparison to conventional HMA, SMA is complex. The materials required are premium, and the costs associated with SMA are at least commensurate. To determine whether the additional costs are justified, it is important to document the quality characteristics of those materials (and projects) that constitute the foundation of Virginia's expanded commitment to SMA.

PURPOSE AND SCOPE

The purpose of this report was to document the SMA "implementation initiative" of VDOT's 2003 and 2004 paving seasons. The report summarizes and presents detailed information on costs and quantities, volumetric properties, compaction, permeability, aggregate quality, and initial functional character of SMA pavements placed during the 2003 and 2004 seasons. It is anticipated that these data will be used as a baseline from which future performance trends can be developed.

METHODS

Quantities and Costs

To understand the scale of the expanded SMA deployment of 2003/2004, the statewide resurfacing schedules and special advertising and awards process (i.e., SAAP) contracts were reviewed and total contracted tonnage and weighted average costs were recorded and summarized.

VTRC Field Testing

A crew from the Virginia Transportation Research Council (VTRC) attempted to make one project visit for every mix placed during the 2003 and 2004 construction seasons. The goal was to gather an independent assessment of the typical quality characteristics of SMA. Each field trip started at the producer's plant, where mix and coarse aggregate samples were collected. The research team typically arrived just prior to plant startup and remained until production was well underway. To permit the entire production and placement train to be in full-scale operation, mix sampling targeted the sixth to eighth truckloads. The sampling involved taking four 50-lb bags of mix. Three of the bags were collected to use with follow-up laboratory tests, and the fourth was placed in a modified cooler to be used for patching core holes.

Once sampling was completed, the VTRC crew followed the truck to the project and began to prepare for a series of field tests. While two technicians were unpacking and preparing equipment near the beginning of the night's paving activity, a third technician caught up to the paving train and located the originally sampled truck. Once the truck had delivered its cargo, the technician allowed for the capacity of the material transfer vehicle (approximately 1 truck) and then marked the approximate beginning of the mat containing the mix from the originally sampled truck.

The VTRC crew continued to prepare testing equipment and marked off a 150-ft test section (approximate limits of 1 truck of mix) while final compaction was underway. Once compaction was completed, the exact core locations were established. These locations were selected using a spreadsheet that incorporated a random number generator and was customized for the anticipated test section length and lane width. A handheld global positioning system recorded the coordinates of each core location. Then, as construction traffic permitted (e.g., to accommodate striping activities), a series of density readings with nuclear and non-nuclear gauges was taken directly over each anticipated core. Once the pavement had cooled adequately (generally less than or equal 150 F), the VTRC core rig was moved onto the fresh mat and positioned over the first core. Prior to coring, field permeability tests were run using an NCAT field permeameter (Cooley and Brown, 2000). Once the permeability tests were completed, cores were extracted. Five cores were taken from each test section. While two technicians conducted the permeability tests and extracted the cores, a third member of the research team filled and compacted the core holes with the hot SMA material from the cooler. Table 2 summarizes the field activities.

Table 2. VTRC Field Activities

Activity/Test	Test Method/Device (as applicable)
Obtain mix samples	See Laboratory Testing
Establish test site	
Locate cores (with GPS)	
Determine nuclear density	Troxler 4640B
Determine non-nuclear density	PQI Model 301 & Troxler 2701
Determine field permeability	NCAT field permeameter
Obtain cores	6-in inside diameter barrel

PQI = Pavement Quality Indicator by Transtech (Transtech, 2004).

VTRC Laboratory Testing

Gyratory Specimens (Truck-Sampled Material)

Laboratory tests included the standard assortment of hot-mix quality assurance tests in addition to a handful of additional exploratory tests. The conventional tests included the preparation of 100-gyration sample pills from which standard volumetric properties were measured or calculated. These properties were established using bulk gravities from saturated surface dry (SSD) tests and an automated vacuum sealing device (ASTM D6752; ASTM International, 2005). In addition to the 100-gyration pills, 50-gyration samples were prepared and a similar series of properties obtained. Table 3 summarizes the information obtained or calculated for the gyratory specimens (or pills).

Table 3. Gyratory Data

Test/Property	Standard Designation
Asphalt Content (%)	Virginia Test Method 102
Voids in Total Mix (%)	Calculated
Voids in Mineral Aggregate (%)	Calculated
Voids Filled with Asphalt (%)	Calculated
Voids in Mix Coarse Aggregate (%)	Calculated
Dust to AC Content (%)	Calculated
Bulk Specific Gravity of Mix	AASHTO T-166 (saturated surface dry) and ASTM D6752 (using CoreLok® by Instrotek®, Inc.)
Effective Specific Gravity of Aggregate	ASTM D2041
Aggregate Specific Gravity	AASHTO T-85
Binder Absorbed (%)	Calculated
Effective Binder Content (%)	Calculated
Density of pill @ 7 gyrations (%)	Calculated

Note: Each property/measurement was determined using four bases: 100-gyration SSD, 100-gyration with vacuum sealing, 50-gyration SSD, and 50-gyration with vacuum sealing.

Cored Specimens

Upon return to the lab, the cored specimens were cleaned and dried and any underlying material was removed using a wet saw. The specimens were used to determine actual achieved density, again using the SSD method and with the CoreLok® device. Each core was also tested for permeability (Virginia Test Method 120) and AC content. Finally, a gradation analysis was performed for each specimen.

Aggregate Samples

In addition to the sampled mix (from trucks) and the cored specimens, coarse aggregate samples were collected from each SMA source on the producer's yard. These samples were used to characterize the flat and elongated (F/E) particle content (ASTM D4791) of the various sources. Results of tests from the raw stockpile were mathematically blended and compared to F/E particle test results for the actual blended material from the sampled mix.

Producer and VDOT District Test Results

At the end of each season's activities, a summary of data was requested from each of the relevant construction districts. The districts supplied volumetric and gradation results for the VDOT labs and the producer. Along with gradation and volumetric data were density tests results and daily production totals.

Ride Quality, Friction, and Texture Measurements

Finally, all SMA sites were tested for ride quality and resistance to skidding. The ride quality testing adhered to the VDOT Special Provision for Rideability and was conducted in accordance with ASTM E950 and Virginia Test Method 106. All testing was conducted within 30 days of completion of the final surface course. Results are reported as international roughness index (IRI) units. Follow-up testing was also performed on the 2003 projects in January, June, and December 2004. Those results are summarized and presented.

In addition to ride quality, most SMA pavements were tested for friction using VDOT's locked wheel skid testing unit (ASTM E274 with the smooth test tire, ASTM E524). Many of the 2003 sites have seen repeated testing to assess seasonal and traffic-wear variation. Initial readings and seasonal trends are presented and discussed.

FINDINGS

Quantity and Costs

Quantity

In 2003, contracts for more than 180,000 tons of SMA were awarded through the normal plant-mix schedules. Seven districts awarded contracts to place SMA with an eighth district receiving bids that were rejected due to excessive material costs. Additionally, more than 75,000 tons of SMA was placed as a result of holdover work from the 2002 paving season. As a consequence of this holdover work, two SMA special provisions were relevant during the 2003 construction season. Table 4 identifies the amount of SMA placed per type, district, and special provision.

In 2004, the maintenance plant-mix schedules and the SAAP contracts combined to include more than 210,000 tons of SMA in six districts. Additionally, several thousand tons of SMA was placed as a result of holdover work from the 2003 paving season in the Richmond and Fredericksburg Districts. Table 5 identifies the amount of SMA placed per type, district and specification. Unlike 2003, all of the SMA placed in 2004 was designed using the 2002 Special Provision for SMA.

Table 4. SMA Contracts Awarded in 2003 (Clark et al., 2004)

District	SMA Placed (tons)		Special Provision
	Surface [Type]	Intermediate [Type]	
Salem	18,700 [12.5 (76-22)]	6,100 [19.0 (76-22)]	2002
Richmond	18,800 [12.5 (70-22)]	11,500 [19.0 (70-22)]	2002
	53,000 [12.5 (70-22)]	29,500 [19.0 (70-22)]	1999
Hampton Roads	8,000 [12.5 (76-22)]		2002
Fredericksburg	14,500 [12.5 (76-22)]		2002
	10,400 [12.5 (76-22)]		1999
Culpeper	12,600 [9.5 (70-22)]		2002
Staunton	40,500 [12.5 (76-22)]	31,500 [19.0 (76-22)]	2002
Northern Virginia	7,200 [9.5 (70-22)]		2002

Table 5. SMA Awarded in 2004 (VDOT, 2005)

District	SMA Placed (tons)		Special Provision
	Surface [Type]	Intermediate [Type]	
Salem	31,600 [12.5 (76-22)]	1,800 [SMA 19.0 (76-22)]	2002
	1,800 [9.5 (70-22)]		2002
Richmond	36,100 [12.5 (70-22)]	23,000 [SMA 19.0 (70-22)]	2002
	6,800 [9.5 (76-22)]		2002
Fredericksburg	21,700 [12.5 (76-22)]		2002
Culpeper	14,000 [9.5 (70-22)] 11,300 [12.5 (70-22)]		2002
Staunton	38,000 [12.5 (76-22)]	10,100 [SMA 19.0 (70-22)]	2002
Northern Virginia	14,300 [9.5 (70-22)]		2002

Costs

The cost for SMA is higher than conventional HMA due to numerous material, design, production and placement differences. The mix itself typically uses higher liquid AC content, higher-quality aggregates, mineral filler, and fibers. From a production and placement standpoint, the plant must operate at a higher temperature, a fiber feeder machine is required, material transfer vehicles (MTV) are mandatory, and paver speeds are generally slower to ensure that density requirements are met.

Table 6 summarizes the weighted (by quantity) average unit costs for the 2003 and 2004 paving seasons, as well as the awarded quantities (statewide) for the 2003 and 2004 paving seasons. Overall, there was a fairly modest average increase in unit price of 86-cents per ton between 2003 and 2004.

Table 6. 2003 and 2004 SMA Surface Mix Unit Costs

Mix Type	Total Tons		Weighted Average Cost	
	2003	2004	2003	2004
SMA 9.5 (70-22)	20,700	30,100	$49.38	$50.21
SMA 9.5 (76-22)	None Used	6,800		$55.60
SMA 12.5 (70-22)	18,800	47,400	$49.20	$49.76
SMA 12.5 (76-22)	108,000	91,300	$57.00	$60.80

Production

With many contractors having limited or no experience with the production and placement of SMA, an analysis was performed to review production rates. Table 7 summarizes daily (or nightly) production totals for the various SMA mixtures placed during the 2003 and 2004 construction seasons. The average values do not include production during test strip placement, but may include short nights due to weather or wrap-up work at the end of projects. The highest single-day placement quantities were achieved during both seasons with an SMA 9.5 mix. The highest production rates for the 2003 season were for projects in which day paving was permitted. The same contractor did however manage to place over 1800 tons of a similar mix on a night-paving job in 2004. Although average daily production was something less than 1000 tons (two-season average of 880 tons/day), production close to or just over 1500 tons per night appeared achievable for nearly every mix.

Table 7. Mix Production

Mix Type	2003 Data			2004 Data		
	No. of Mixes	Daily Production		No. of Mixes	Daily Production	
		Average (Tons)	High (Tons)		Average (Tons)	High (Tons)
SMA 9.5 (70-22)	2	1122	2123	7	707	1807
SMA 12.5 (70-22)	2	1053	1646	5	1091	1580
SMA 12.5 (76-22)	9	796	1833	7	760	1365
SMA 19.0 (70-22)	6	965	1766	3	1014	N/A
SMA 19.0 (76-22)	1	846	1122	1	0	0
All Mixes[a]	20	886	1788	23	875	1584

[a]Weighted averages, N/A = data not available.

Volumetric Mix Properties

The volumetric properties of HMA mixes provide key indicators of produced quality and corresponding expected long-term performance. Among the properties reviewed were AC content, voids in mineral aggregate (VMA), voids in coarse aggregate for the mix (VCA_{mix}), and voids total mix (VTM). The following sections summarize these properties as measured by the producer, the VDOT district materials laboratories, and as measured from one independent sample taken by VTRC. Although VTRC produced a similar series of test results for 50-gyration level samples, the presented VTRC results are for the 100-gyration specimens and the SSD method for bulk density measurement.

AC Content

A fundamental attribute of SMA is elevated levels of liquid AC. Table 8 reflects average AC content for each mix type over both seasons. Statewide, there was reasonable agreement between the contractor and the VDOT district. VTRC samples provided similar trends but were too limited to offer a comparable degree of agreement.

The standard deviations for the 9.5 (70-22) and 12.5 (76-22) mixes appear to have degraded for the 2004 season, especially as reported by the producer. Unfortunately, the data from 2004 were not as complete as those from 2003. For that reason, drawing sweeping conclusions is not recommended.

Table 8. AC Content (% by weight) for SMA: 2003 and 2004

Mix Type/ Specification Requirement	Producer				VDOT District				VTRC	
	2003		2004		2003		2004		2003	2004
	Avg. %	S.D.	Avg. %	S.D.	Avg. %	S.D.	Avg. %	S.D.	Avg. %	Avg. %
SMA 9.5 (70-22)/6.8%[a]	6.56	0.18	6.68	0.29	6.61	0.16	7.03	0.32	6.55	7.02
SMA 12.5 (70-22)/6.5%	6.87	0.20	6.80	0.18	6.90	0.34	6.70	0.28	7.11	7.10
SMA 12.5 (76-22)/6.5%	6.97	0.20	6.85	0.79	7.01	0.25	6.79	0.34	7.27	7.08
SMA 19.0 (70-22)/5.5%	5.95	0.20	6.00	0.20	5.96	0.33	5.70	0.20	6.05	N/A
SMA 19.0 (76-22)/5.5%	5.86	0.29	N/A	N/A	5.75	0.18	N/A	N/A	6.04	5.70

N/A = data not available.
[a] SMA 9.5 (70-22) mixes were produced with aggregates that have very heavy specific gravities (> 3.0). Although these AC content values appear low (expressed by weight), the actual volume of AC easily meets intended targets.

Voids in Mineral Aggregate

A summary of VMA is presented in Table 9. Once again, agreement between the producer and VDOT was very good. VMA, which better depicts the volumetric character of the mix components (unlike % by weight AC content), reflects an expected step down with increasing nominal maximum aggregate size.

Table 9. Voids in Mineral Aggregate (VMA)

Mix Type/ Specification Requirement	Producer				VDOT District				VTRC	
	2003		2004		2003		2004		2003	2004
	Avg. %	S.D.	Avg. %	S.D.	Avg. %	S.D.	Avg. %	S.D.	Avg. %	Avg. %
SMA 9.5 (70-22)/18.0%	19.1	1.11	18.5	0.80	19.0	0.97	18.5	0.80	18.8	18.30
SMA 12.5 (70-22)/18% (17% for 1999)	18.1	0.48	18.1	0.68	18.5	1.05	18.2	0.73	18.5	17.20
SMA 12.5 (76-22)/18% (17% for 1999)	17.7	0.63	17.9	1.48	18.1	0.89	18.2	1.20	19.2	18.65
SMA 19.0 (70-22)/17% (16.0% for 1999)	16.5	0.81	16.4	0.60	16.5	0.69	15.9	0.40	17.7	N/A
SMA 19.0 (76-22)/17% (16.0% for 1999)	16.2	0.58	N/A	N/A	16.2	0.48	N/A	N/A	18.6	5.70

N/A = Data not available.

Voids in Coarse Aggregate

VCA is used to assess skeleton stability for SMA mixes. This is done by comparing the VCA of the coarse aggregate only (the dry-rodded condition or VCA_{DRC}) to the VCA of the mix (VCA_{mix}). As long as the VCA_{mix} is less than or equal to the VCA_{DRC}, a mix is considered to have adequate stone-on-stone contact. The average VCA values for 2003 and 2004 are summarized in Tables 10 and 11. In general, these results suggest that stone-on-stone contact is of little concern for the smaller (9.5 mm) and larger (19.0 m) SMA mixes. The ratio of VCA_{mix} to VCA_{drc} was much closer to unity, however, for the 12.5 mm mixes. In several instances, the VTRC samples identified mixes that actually fail the VCA criterion. There were no reports, however, of unstable 12.5 mm SMA mixes.

Table 10. Voids in Coarse Aggregate: 2003 Season

Mix Type	VCA_{drc}	Producer		VDOT District		VTRC
		VCA_{mix}	VCA_{mix} (S.D.)	VCA_{mix}	VCA_{mix} (S.D.)	VCA_{mix}
SMA 9.5 (70-22)	42.1	36.2	0.69	36.6	0.91	35.1
SMA 12.5 (70-22)	43.1	40.7	0.73	41.5	1.26	40.3
SMA 12.5 (76-22)	42.3	40.5	1.73	41.1	1.89	42.1
SMA 19.0 (70-22)	42.5	35.8	1.23	35.3	2.11	34.2
SMA 19.0 (76-22)	42.9	34.3	1.42	32.9	1.25	34.2

Note: Specification requirement: VCA_{mix} less than or equal VCA_{drc}.

Table 11. Voids in Coarse Aggregate: 2004 Season

Mix Type	VCA_{drc}	Producer		VDOT District		VTRC
		VCA_{mix}	VCA_{mix} (S.D.)	VCA_{mix}	VCA_{mix} (S.D.)	VCA_{mix}
SMA 9.5 (70-22)	43.7	36.1	1.8	36.0	1.2	39.3
SMA 12.5 (70-22)	43.5	40.2	1.6	41.0	1.7	42.9
SMA 12.5 (76-22)	41.7	39.6	1.5	40.4	2.1	43.1
SMA 19.0 (70-22)	42.9	37.5	1.8	37.3	1.8	N/A
SMA 19.0 (76-22)	N/A	N/A	N/A	N/A	N/A	38.3

N/A = Data not available.

Note: Specification requirement: VCA_{mix} less than or equal VCA_{drc}.

Voids in Total Mix

VTM are presented in Table 12. With the exception of the VTRC data, the VTM values from year to year were consistent and within the criteria set for production. The test results from the VTRC sampling (and testing) indicated considerably lower voids in 2004 than in 2003.

Table 12. Voids in Total Mix

Mix Type	Producer				VDOT District				VTRC	
	2003		2004		2003		2004		2003	2004
	Avg. %	S.D.	Avg. %	S.D.	Avg. %	S.D.	Avg. %	S.D.	Avg. %	Avg. %
SMA 9.5 (70-22)	3.5	1.32	2.8	1.1	2.9	1.33	2.5	1.2	2.9	1.7
SMA 12.5 (70-22)	3.0	0.59	3.0	0.7	3.2	1.19	2.9	0.8	2.9	1.5
SMA 12.5 (76-22)	2.4	0.66	2.6	1.1	2.7	1.07	3.0	1.4	3.2	2.6
SMA 19.0 (70-22)	2.5	0.72	2.5	0.5	2.7	0.98	2.7	0.6	3.9	N/A
SMA 19.0 (76-22)	2.8	0.71	N/A -	N/A	2.9	1.06	N/A-	N/A	5.0	2.2
All Mixes	2.7	0.74	2.7	0.9	2.8	1.08	2.8	1.0	3.4	2.0

N/A = Data not available.

Note: Specification requirements: design target = 3.5, production target = 2.5–4.5 (1999), 2.5–4.5 (2002 surface), 2.0–4.0 (2002 intermediate).

Field Density

Under normal circumstances, the producer (under supervision of the engineer) provides the sole measure of daily field density using five plugs that are dry-cut from the freshly placed and compacted mat. Unless problems are suspected or observed, no additional measurements of density are made. Since the VTRC field sampling also included extracting five wet cores from a selected test section, an additional independent measure of field density was available for most mixes.

Table 13 provides the average field density data as measured by the producer and VTRC. Overall, the producer test results and those determined at the one-time VTRC visit were approximately 0.5 percentage point apart. Typically, the contractor achieved target density values for both seasons, whereas the limited VTRC testing identified some potential under-compaction issues with the SMA 9.5 (70-22) and SMA 19.0 (70-22) mixes in 2003. Additional VTRC sampling in 2004 found that the SMA 9.5 compaction levels had improved slightly to within specification limits. Unfortunately, VTRC testing failed to capture any density results for the SMA 19.0 mixes in 2004.

Table 13. Field Density Measurements

Mix Type	2003			2004			Average	
	Producer		VTRC	Producer		VTRC	Producer	VTRC
	Average (%)	S.D.	Average (%)	Average (%)	S.D.	Average (%)	Weighted Avg. %	Weighted Avg. %
SMA 9.5 (70-22)	96.0	1.1	93.2	94.7	1.3	95.0	95.0	94.6
SMA 12.5 (70-22)	94.8	0.6	94.2	94.8	1.0	94.8	94.8	94.6
SMA 12.5 (76-22)	95.2	1.0	95.7	95.2	1.3	93.6	95.2	94.8
SMA 19.0 (70-22)	94.7	0.6	93.6	95.3	1.3	N/A	94.9	93.6
SMA 19.0 (76-22)	96.3	1.4	96.0	N/A	N/A	95.1	96.3	95.6
All Mixes	95.1	0.9	94.6	95.0	1.2	94.6	95.0	94.6

N/A = data not available.
Note: Specification requirements: 94% minimum/98% maximum for 100% payment.

Field/Lab Permeability

Typically, the results of the permeability testing were conclusive. That is, a test location or specimen either passed VDOT's proposed permeability limit (150 x 10^{-5} cm/s) in accordance with Virginia Test Method 120) or failed it by a significant margin. For that reason, average permeability numbers for a given mix would reveal very little (very high failing numbers tend to result in inflated average numbers). Consequently, the number of locations/cores that passed among the five tests conducted is reported and not the average permeability value.

Tables 14 and 15 supply the VTRC permeability test results for 2003 and 2004, respectively. In addition to permeability, the tables report average measured void level (SSD) for each mix type and the total number of cores per type with void levels less than or equal 6.0%. The exaggerated surface texture of the 19.0 mm mixes made it nearly impossible to seat (and seal) the field permeameter. For that reason, the 2003 field results for the 19.0 mm mixes are considered suspect at best (field tests were not attempted in 2004). The lab tests, however, should provide a fair indicator of permeability.

Table 14. 2003 Core Permeability and Void Levels

Mix	Total Cores Tested	Permeability		Core Void Level	
		Field, Number Passing	Lab, Number Passing	Average (%)	Number Passing (<6%)
SMA 9.5 (70-22)	10	4	5	6.8	4
SMA 12.5 (70-22)	10	5	4	5.8	5
SMA 12.5 (76-22)	35	25	30	4.8	29
SMA 19.0 (70-22)	15	0	4	6.2	8
SMA 19.0 (76-22)	5	0	5	4.0	5

Note: Proposed permeability limit for Superpave surface mixes = 150 x 10^{-5} cm/s (Virginia Test Method 120).

Table 15. 2004 Core Permeability and Void Levels

Mix	Total Cores Tested	Permeability		Core Void Level	
		Field, Number Passing	Lab, Number Passing	Average (%)	Number Passing (<6%)
SMA 9.5 (70-22)	10	5	10	5.0	7
SMA 12.5 (70-22)	10	5	6	5.0	4
SMA 12.5 (76-22)	45	30	31	5.4	28
SMA 19.0 (70-22)	N/A	N/A	N/A	N/A	N/A
SMA 19.0 (76-22)	5	NT	2	4.9	4

N/A = Data not available, NT = not tested.
Note: Proposed permeability limit for Superpave surface mixes: 150 x 10^{-5} cm/s (Virginia Test Method 120).

The SMA 12.5 (76-22) mixes were the most consistent performer statewide with nearly 70% (55 of 80) of the field locations and 75% (61 of 80) of the cores meeting the proposed permeability requirements for Superpave surface mixes. The 9.5 mm mixes saw the most substantial improvement from 2003 to 2004 (50% passing in 2003 to 100% in 2004). The 19.0 mm mixes appear to have the most difficulty with permeability. Including the handful of cores collected in 2004, less than 50% of 19.0 mm mixes passed VDOT's proposed limit for permeability.

This core-by-core review of void level also offers insight into achieved compaction levels for SMA. Bear in mind that by comparison to "production" data, these results are extremely limited and may not be representative of general levels of compaction. Still, it is somewhat alarming to note that a full one-third (51 of 145) of the cores taken (via VTRC testing) indicated a failure to reach target levels of compaction. This trend did not appear more prominent in any single mix type.

Flat and/or Elongated Particles

The VTRC sampling also included material from each of the coarse aggregate stockpiles in the job mixes. Standard aggregate F/E particle tests were conducted on both the raw aggregate material and the mixed material after a furnace burn. Table 16 summarizes the results by mix type. The calculated values mathematically blend test results from the raw aggregate material to provide theoretical F/E particle content for the mix. The mix values reflect the test results from the extracted coarse aggregate of the already blended hot-mix. Generally speaking, the 5 to 1 criterion was not an issue, and most stockpiles met the F/E particle criterion for allowable 3 to 1 content. However, for the 2003 data, the mix and one source material exceeded the 3 to 1 criterion for one SMA 19.0 (70-22) mix, and in at least two instances, one source material failed the 3 to 1 criterion for SMA 12.5 (76-22) mixes. For 2004, the overall F/E particle results were much improved, and only one tested source exceeded the 3 to 1 criterion. In the *calculated* blend, the average F/E particle result dropped by 3.6%. In the *mix*, the 2004 mixes contained 5.2% less F/E particles than in 2003.

Table 16. VTRC Flat and Elongated Particle Test Results for 2003

Mix Type	No. of Mixes	No. of Aggregate Sources	Calculated Value 5 to 1	Mix Value 5 to 1	Calculated Value 3 to 1	Mix Value 3 to 1
SMA 9.5 (70-22)	2	4	1.3	0.5	14.0	12.8
SMA 12.5 (70-22)	2	4	0.4	1.1	14.4	12.0
SMA 12.5 (76-22)	7	34	0.7	0.5	12.5	12.4
SMA 19.0 (70-22)	4	10	0.6	0.6	15.5	15.0
SMA 19.0 (76-22)	1	3	1.0	1.5	16.2	14.7
All mixes	16	55	0.8	0.8	14.5	13.4

Note: 5 to 1 tolerance was 5%, 3 to 1 tolerance was 20%.

Table 17. VTRC Flat and Elongated Particle Test Results for 2004

Mix Type	No. of Mixes	No. of Aggregate Sources	Calculated Value 5 to 1	Mix Value 5 to 1	Calculated Value 3 to 1	Mix Value 3 to 1
SMA 9.5 (70-22)	3	6	0.6	0.1	10.4	9.8
SMA 12.5 (70-22)	2	3	0.4	0.5	14.9	8.1
SMA 12.5 (76-22)	8	18	0.3	0.2	9.4	7.3
SMA 19.0 (70-22)	1	2	1.2	0.4	16.7	11.5
All mixes	14	29	0.5	0.2	10.9	8.2

Note: 5 to 1 tolerance was 5%, 3 to 1 tolerance was 20%.

Functional Characteristics

Ride Quality

Initial Testing

In 2003, a total of 22 sites consisting of 185 lane-miles were tested for roughness after completion of paving. The majority of the sites were located on interstate routes (18 sites), and the remainder was located on four-lane divided primary routes (4 sites). All of the interstate sites and one primary site, U.S. 58 in Hampton Roads, were 12.5 mm surface mixes. The remaining three primary sites, in Culpeper and Northern Virginia, were 9.5 mm surface mixes.

In 2004, a total of 30 sites consisting of 202 lane-miles were tested for roughness after completion of paving. Twenty-four of these sites were on interstate routes, and the remainder was on four-lane divided primary routes (6 sites). All but one of the interstate sites (I-66 in the Culpeper District) and 2 primary sites (U.S. 360 in the Richmond District) were 12.5 mm surface mixes. The remaining 5 primary sites, in Culpeper, Salem, and Northern Virginia, were 9.5 mm surface mixes.

Table 18 summarizes the final surface IRI (i.e., "after IRI") measurements for the 2003 and 2004 SMA projects. In 2003, the weighted statewide average was 66 in/mi, with a high of 87 in/mi and a low of 46 in/mi. Both the highest and lowest project-long IRI values were found among the three projects (and 26.34 mi) that represented the SMA 9.5 (70-22) mixes. In 2004, the weighted statewide average was 62 in/mi, with a low of 42 in/mi on I-81 in the Staunton District and a high of 88 in/mi on U.S. 15 in the Northern Virginia District. Once again, the SMA 9.5 (70-22) projects had the broadest range of IRI values (88 to 45 in/mi) although achieved smoothness varied some for all of mix types.

Overall, the ride quality results for SMA projects improved from 2003 to 2004, with the IRI decreasing from 66 in/mi to 62 in/mi.

Table 18. Average Final-Surface IRI by Mix Classification

Mix	2003		2004	
	Average IRI (in/mi)	Lane Mileage (mi)	Average IRI (in/mi)	Lane Mileage (mi)
SMA 9.5 (70-22)	61.3	26.34	65.8	33.00
SMA 12.5 (70-22)	76.3	55.89	69.6	31.24
SMA 12.5 (76-22)	61.5	102.19	59.2	133.33

Special Provision for Rideability

The ride quality test results were also used to apply VDOT's Special Provision for Rideability, which incorporates incentives and disincentives for smoothness/roughness of the final surface. Table 19 shows the results of the amount paid in incentives/ disincentives for the SMA rideability projects in 2003 and 2004. It also shows the average percentage improvement

Table 19. Rideability Incentives/Disincentives ($) and Percent Improvement

District	2003		2004	
	Incentive/ Disincentive	% Improved[a]	Incentive/ Disincentive	% Improved[a]
Salem	16,863.83	32	(58,902.89)	9
Richmond	(46,284.70)	17	(1,824.62)	17
Hampton Roads	4,267.50	24	N/A	N/A
Fredericksburg	3,581.00	43	(20,327.00)	22
Culpeper	40,164.68	48	(16,134,18)	25
Staunton	(50,540.24)	14	79,195.89	24
Northern Virginia	(17,560.13)	27	(20,430.77)	34
Total	(49,508.06)	25	(38,423.61)	19

[a]Reflects reduction in roughness from original surface.

based on the results of the before and after rideability testing. As could be expected, the sites with the smallest percent improvement received the greatest disincentives.

In 2003, three districts assessed net disincentives for ride quality and four were able to distribute net incentives. Statewide, a net disincentive of approximately $50,000 of a total contract value (surface mix only) of $8.1 million was assessed. For 2004, with the exception of the Staunton District, all districts assessed net disincentives. Statewide, a net disincentive of approximately $38,000 of a total contract value (surface mix only) of $11.5 million was assessed. The $12,000 reduction in disincentive between 2003 and 2004 reflects the slight overall improvement in achieved smoothness.

Follow-up Ride Quality Testing

The mixes placed in 2003 were tested again for ride quality in January, June, and December of 2004. A general trend (shown in Figure 1) shows a slight increase and subsequent

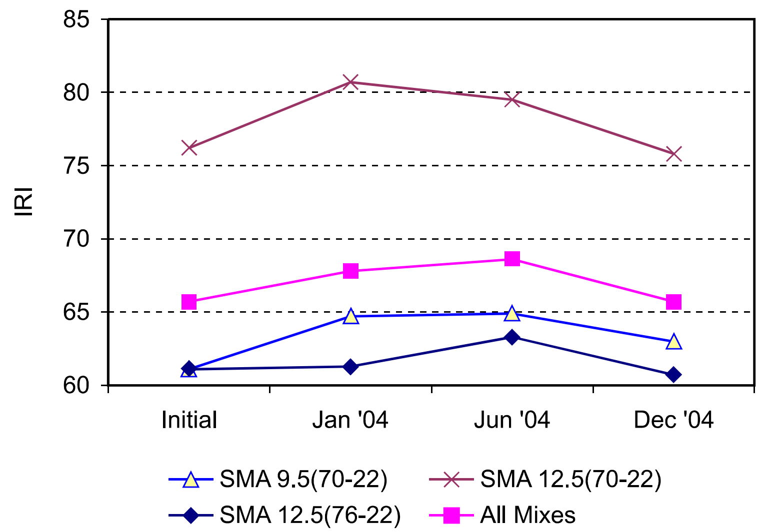

Figure 1. IRI Change for 2003 Mixes

decrease in IRI through a year to 18 months of service. The overall average IRI from December 2004 is nearly identical to the IRI immediately after placement in 2003. Additional testing is currently underway.

Friction

With the high AC content (and high film thickness) indicative of SMA mixes, early-age skid resistance was a concern. Friction testing was conducted on the SMA sites beginning in September and October of 2003 and continuing through the middle of 2005.

Early-Age Friction

Figure 2 depicts the average friction measurements (skid number, or SN) for the first 4 to 6 months of service life of the 2003 SMA surface mixes. Initial tests indicated significantly lower numbers for the 9.5 mm mixes (average SN = 34.0) as compared to the 12.5 mm mixes (average SN = 44.1). Subsequent tests have shown a significant increase in available friction for all mix types. The largest increase occurred with the 9.5 mm mixes, which increased from a SN of 34.0 to 46.1 between October 2003 and January 2004. The SN for the 12.5 mm mixes increased more moderately, from 44.1 in October 2003 to 49.5 in February 2004.

Figure 3 relates to friction in the first year of service life for the 2004 SMA mixes. The initial tests showed the average SN to be lowest for the SMA 12.5 (76-22) mixes (average SN = 38.0) and highest for the SMA 12.5 (70-22) mixes (average SN = 45.5). The average SN for the SMA 9.5 (70-22) mixes was 41.0 and closest to the overall average of 39.9. Subsequent tests on these projects show significant early-age increases in friction for all mix types and then decreases in SN between January and July 2005.

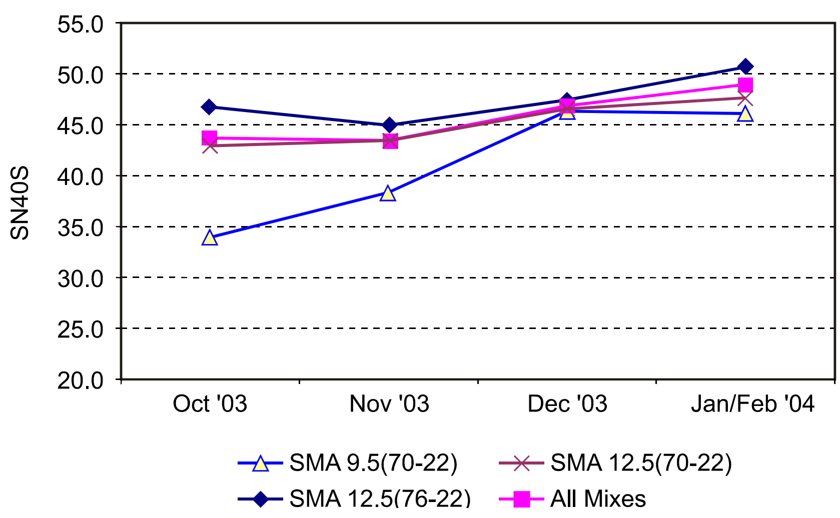

Figure 2. Friction Change with Accumulated Traffic/Weather for 2003 Mixes. SN40S = Skid number from lock-wheeled friction tester (ASTM E-274) equipped with smooth test tire (ASTM E524).

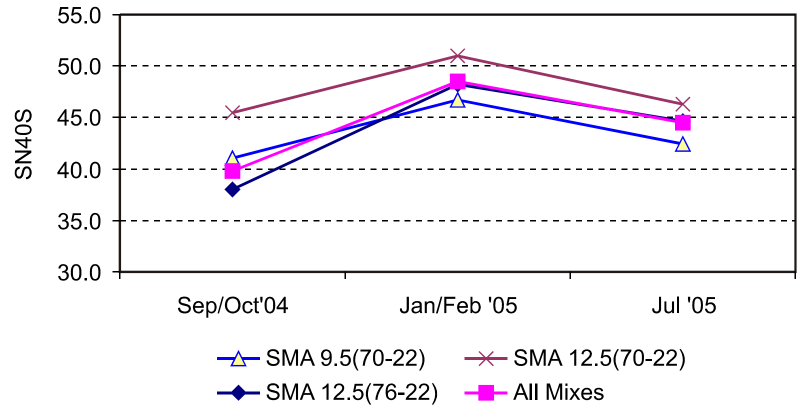

Figure 3. Friction Change with Accumulated Traffic/Weather for 2004 Mixes

Longer-Term Friction

Since the first three cycles of friction testing with the 2003 surface mixes, addition testing has been performed in May and October 2004 and January and June 2005. These results, reported in Figure 4, show a clear downward trend in friction in the warmer months (Sep/Oct 04, Jul 05) and an upward trend in the colder months (Jan 05). The downward trend is most pronounced for the SMA 9.5 (70-22) mixes, which registered the lowest initial SN values (34.0). Overall, the friction numbers are good and have continued to increase with time. The initial low readings at a few sites were found very shortly after paving and have continued to increase as traffic wears off the initial film and exposes more of the aggregate micro-texture. There is at least once example in which warm-weather mortar flow may be reducing wheelpath macrotexture on a 9.5 mm mix. This phenomenon was identified and discussed in more detail in a recent research report on hot-mix uniformity (McGhee, 2005). VDOT's Pavement Design and Evaluation Section and asphalt pavement field engineers continue to work with district materials personnel to monitor the friction on this and other SMA projects.

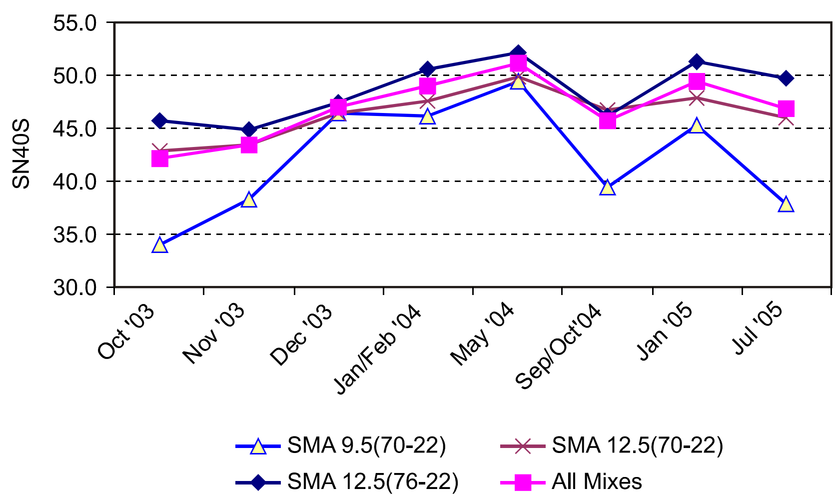

Figure 4. Longer-Term Friction for 2003 Mixes. Note that changes to VDOT's SMA specification (Fall 2004) permit decreased AC volume and require increased –200 material. These changes are expected to eliminate the warm-weather mortar flow observed with the SMA 9..5 mixes from 2003.

CONCLUSIONS

- *SMA is expensive.* It is used on Virginia's highest priority facilities and placed under the most challenging conditions. It requires premium materials, sophisticated production processes and specialized placement equipment. The performance expectations are (and should be) extremely high.

- *Average daily production for SMA is approximately 900 tons/day.* However, production close to or just over 1,500 tons per night appears achievable for nearly every mix (with "typical" project constraints, which included night paving).

- *Although results were mixed, the control of liquid AC content for surface mixes (as evidenced through producer standard deviations) appears to have decreased between the 2003 and 2004 seasons.*

- *Stone-on-stone contact is being achieved with consistency.*

- *The two SMA surface mixes (9.5 mm and 12.5 mm) have generally good (i.e., low) permeability. Many of the 19.0 mm mixes, however, would have difficulty passing VDOT's proposed limit for permeability of Superpave surface mixes.*

- *In contrast to the acceptable average field density results as reported by the producers, the core data from VTRC testing indicates an alarming concentration (1 in 3) of under-compacted material.*

- *The F/E particle content of the coarse aggregate sources (and blends) was much improved for the 2004 season.* Producers are finding sources and/or applying aggregate handling techniques that ensure that aggregates meet shape requirements for SMA.

- *Achieved smoothness for SMA improved and net disincentives dropped slightly in 2004 as compared to 2003.*

- *Lower early-age friction improves rapidly under traffic for SMA.* SMA mixes also exhibit prototypical seasonal variation, with the lowest friction in the summer months. The two 9.5 mm mixes from 2003 (heavy stone and high relative volume of AC) continue to exhibit the most significant dips in seasonal friction.

RECOMMENDATIONS

1. *VTRC should work with VDOT's asphalt pavement field engineers to establish a comparative series of conventional hot-mix projects (i.e., Superpave mixes) in order to track relative performance and life-costing aspects of the two hot-mix alternatives (SMA versus Superpave).*

2. *VDOT quality assurance and producer quality control personnel should closely monitor liquid AC content for SMA to ensure adequate control.*

3. *VTRC, VDOT's Materials Division, and the asphalt industry should work together to promote a better understanding of testing procedures, variability, and uniformity relating to compaction of SMA.*

4. *The Pavement Design and Evaluation Section of VDOT's Materials Division should continue to monitor friction for the smaller stone (9.5 mm) SMA mixes.*

5. *VTRC, VDOT's Materials Division, and the asphalt industry should work together to review and revise the SMA applications guidelines (i.e., when and where to use SMA, what mix should be used, etc.).*

COSTS AND BENEFITS ASSESSMENT

A recent publication issued by the National Asphalt Pavement Association with the Federal Highway Administration (Hughes, 1999) presents a life-cycle cost analysis that demonstrates a $29,000 per mile lifetime savings when SMA is used instead of conventional dense-graded HMA (on heavily trafficked roads). SMA appears to have established itself as a natural fit for Virginia's highest priority roadways. For 2005, contracts calling for nearly 475,000 tons of SMA were awarded (VDOT, 2005). That accounts for 14% of the total quantity and 18% of the costs associated with a statewide hot-mix resurfacing program worth $164 million. Of course, the materials used to produce SMA are still premium and the practices applied to place it are very expensive. Carefully documenting (or baselining) today's experiences and thoroughly understanding the consequences in terms of life costing are important keys to the continued successful deployment of the best HMA technologies for Virginia. If the costs savings identified by the National Asphalt Pavement Association continue to hold true and are applied to just the 14% of VDOT's annual program allotted to SMA in 2005 (approximately 500 lane-miles), the fruits of this research can contribute to more than $14 million per year in savings.

ACKNOWLEDGMENTS

Research staff at VTRC in cooperation with VDOT's Materials Division conducted this project. The project would not have been possible without the efforts of Troy Deeds, VTRC Asphalt Mixture Lab Manager, and numerous individuals in the district materials offices and asphalt plants from around the state.

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