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Performance Evaluation of Thin Wearing Courses Through Scaled Accelerated Trafficking

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Test results from more than 100,000 wheel load applications of the MMLS3 showed that the thin wearing courses underwent various degrees of permanent deformation depending on their compacted air void content. According to the protocol guidelines developed for the evaluation of permanent deformation and moisture damage when using the MMLS3, most of the mixtures performed well. One exception was a coarser dense-graded material with a high amount of recycled asphalt pavement. No indication of fatigue cracking or other distress was observed for any mixture during or after testing.

The study supports use of the SM-4.75 mixture on low- to medium-traffic roadways and for maintenance and/or preservation applications. It further recommends that the Virginia Department of Transportation apply the methods demonstrated through this research to assess better the stability of experimental wearing course mixtures in advance of wider spread field applications.

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ABSTRACT

The primary objective of this study was to evaluate the permanent deformation (rutting) and fatigue performance of several thin asphalt concrete wearing courses using a scaled-down accelerated pavement testing device. The accelerated testing was conducted using a model mobile load simulator (MMLS3). Field testing with the MMLS3 was conducted on a 4.75-mm nominal maximum aggregate size dense-graded mixture installed at the Turner-Fairbank Highway Research Center. This mixture (designated SM-4.75), two other conventional dense-graded mixtures, and a thin gap-graded mixture were also used to prepare specimens for laboratory rutting tests using the MMLS3.

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FINAL REPORT

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INTRODUCTION

The Virginia Department of Transportation's (VDOT) statewide performance target of less than 18% deficiencies on interstate and on primary systems (both flexible and rigid) was exceeded by more than 6% by the end of 2011 (VDOT, 2012), but efforts were made to remedy this situation. According to the data from VDOT's 2012 *State of the Pavement* annual report, about 17.1% of the interstate network and 18.9% of the primary network were found to be in a deficient condition (VDOT, 2012). Concurrently, traditional maintenance resurfacing activities that typically involve a periodic placement of a 1.5-in to 2-in layer of asphalt concrete (AC) are becoming costly as construction material prices are soaring and revenues are declining. For this reason, pavement engineers are seeking affordable new ways to address structurally adequate pavements with lower cost preservation treatments. Their primary objective is to prevent more pavements from becoming deficient through the use of an efficient and sustained preservation program.

Currently, nearly all departments of transportation and state highway agencies use some kind of conventional preservation alternatives that may offer a longer service life with improved functional character. These alternatives range from crack filling/sealing to microsurfacing, to slurry/chip seals, to AC thin/ultrathin overlays. Typically, several of these restoration techniques are appropriate alternatives, especially when no structural improvement is necessary and the functional character is consistent with expectations. Nonetheless, with the exception of latex-modified slurry seals, thin cold-mix and chip seals are not typically applied to high-priority roadways when state agencies can afford a more "substantial" option like thin layers of plant-produced AC.

For projects where an AC material placed at a thickness of 1 in or less is desired, VDOT has few lower cost options. On interstate and other high-volume routes, VDOT has employed thin hot-mix AC overlays (THMACOs) to preserve the structure and usually improve the functional characteristics of a pavement (Tate and Clark, 2004). In an attempt to develop a material that can take advantage of the lower cost finer fractions of the stone-crushing process, VDOT is currently exploring a new classification of dense-graded mixture designated SM-4.75, which uses a 4.75 mm nominal maximum aggregate size (NMAS). In addition to finer aggregates, this mixture incorporates neat and polymer-modified binders and can be placed in much thinner applications. Unfortunately, outside the developmental work conducted at the National Center for Asphalt Technology (NCAT) (James et al., 2003; West et al., 2011) and anecdotal experience from the use of similar mixtures in other states (Suleiman, 2011; Zaniewski and Diaz, 2004), there is little quantitative performance data on SM-4.75–type mixtures in Virginia. A slightly coarser but more conventional preservation alternative is VDOT's SM-9.0 mixture. This fine surface mixture is usually used in low-volume pavements with little or no heavy vehicle traffic. However, beyond parking areas and subdivision streets, the SM-9.0 mixture also has limited application in Virginia.

PURPOSE AND SCOPE

The primary objective of this study was to evaluate the permanent deformation (rutting) and fatigue performance of several thin AC wearing courses using a scaled-down accelerated pavement testing device. Testing was initially aimed at the experimental ultra-fine, dense-graded surface mixture (i.e., the SM-4.75 mixture) and the THMACO materials. Because of the limited field availability of these two mixtures, two additional (and readily available) mixtures were selected for laboratory accelerated testing: an SM-9.5 and an SM-12.5 mixture, both of which contain a high amount (about 30%) of recycled asphalt pavement (RAP). On-site fatigue testing of the SM-4.75 mixture was also conducted at the Federal Highway Administration's Accelerated Loading Facility (ALF) at the Turner-Fairbank Highway Research Center (TFHRC) in McLean, Virginia.

As the focus of VDOT has shifted toward pavement preservation, this work supports a broader research program underway at the Virginia Center for Transportation Innovation and Research (VCTIR) to compare and catalog the expected performance of thin wearing course alternatives. In addition, the work complements related full-scale testing being conducted at TFHRC. The results from this accelerated testing program will be used to establish rut depth criteria for use with the model load simulator in ranking the performance of thin AC wearing courses.

METHODS

Description of VDOT's Thin Asphalt Concrete Wearing Courses

Dense-Graded Mixtures for Surfaces

Dense-graded mixtures are the most common mixture technology used by VDOT. They are defined by a uniform distribution of aggregate sizes along the maximum density line.

Depending on whether the aggregate gradations are above or below the maximum density line, these mixtures are considered to be fine or coarse graded.

The SM-4.75 mixture is a newly developed and very fine dense-graded mixture that was placed at TFHRC and in limited applications on secondary roads around Virginia. Thin lifts (1 in or less) of the SM-4.75 mixtures can help to restore ride quality, level surface defects, provide a use for excess aggregate screenings, and provide an economical wearing surface for low - volume roadways (James et al., 2003; Suleiman, 2011; West et al., 2011; Zaniewski and Diaz, 2004). Research conducted at NCAT has provided initial criteria for the design of such small-size aggregate surface mixture (James et al., 2003).

The SM-9.5 mixture is a fine to medium 3/8-in (9.5-mm) NMAS surface mixture generally placed in 1.5-in (40-mm) lifts and has a relatively low permeability. It is usually used in surface applications on interstate and primary roads. In this study, two SM-9.5 mixtures were tested: an SM-9.5A (A denoting a softer binder) and an SM-9.5D (D denoting a stiffer binder) with high amounts of RAP (i.e., 25% and greater). The SM-12.5 mixture is considered a medium to coarse 0.5-in (12.5-mm) NMAS mixture and is generally placed at 2 in (50 mm) as a final wearing course.

Gap-Graded Mixtures for Surfaces

Gap-graded mixtures rely on stone-on-stone contact between coarse aggregate particles to serve as the mixture structure. An absence of mid-sized particles (a gradation gap) makes room for fines and higher levels of liquid asphalt binder, which promotes mixture durability (McGhee et al., 2009). Stone matrix asphalt is one common gap-graded mixture. VDOT's THMACO, which is an ultrathin bonded wearing course, is another example of a gap-graded mixture. THMACO is a fine to medium 3/8-in (9.5-mm) NMAS surface mixture generally placed in ¾-in (19-mm) lifts. It is applied atop a polymer-modified emulsion membrane and used for final surface applications as a functional overlay on flexible and rigid pavements. THMACO is primarily used for pavement preservation or as new surface during roadway construction and does not have an air void content requirement. Some of its functions are to restore pavement friction, improve ride quality by reducing noise and water spray, and seal the pavement surface and prevent water infiltration (Tate and Clark, 2004).

General Characteristics of Mixtures

For maintenance overlays, traffic levels normally determine the mixture and binder type. When selecting the binder type, VDOT uses letters to designate asphalt binders in contracts, specifications, and special provisions. For the dense-graded mixtures, the letters *A, D,* and *E* are used to identify the appropriate asphalt binder. In general, the stiffness of a mixture increases from A to E, with A being the softest. The A designation suggests an effective binder performance grading of PG 64-22 used for surface mixtures that will experience up to 3 million cumulative equivalent single-axle loads (ESALs) over a specified service life. These mixtures are expected to perform acceptably in low to medium traffic loading conditions. The D designation, which corresponds to a binder performance grading of PG 70-22, is intended for surface mixtures that will experience between 3 million and 10 million ESALs over an anticipated service life (usually 20 years). Mixtures in this category should perform adequately in medium to high traffic loading conditions.

For specialty mixtures, such as THMACO, a polymer-modified binder performance grading of PG 70-28 is required. This binder is used to provide an adequate resistance to thermal cracking and minimize the reflective cracking for mixtures placed over jointed concrete pavement.

Equipment Used

The accelerated loading required to assess the permanent deformation and durability characteristics of the subject materials was applied with a one-third-scale (1/3) unidirectional model mobile load simulator (MMLS3). This equipment applies realistic rolling wheel contact stresses to evaluate the performance of various asphalt mixtures. The MMLS3, depicted in Figure 1, was derived from the 1:10 scale model that was used mostly in the field to monitor the rutting potential of various mixtures (Bhattacharjee et al., 2004; Hugo, 2000; Hugo et al., 1999; Smit et al., 2003). The machine can be used either in the field by placing it directly on the pavement or in the laboratory on a model pavement structure of various sizes and compacted layers located in a specially constructed mold.

In some cases, asphalt samples that are about to be evaluated for different properties are placed directly on various types of materials, typically aluminum, nylon, neoprene, or steel or a combination(s) thereof, that provide strengths and moduli similar to or greater than those of the actual pavement layers. The MML3 used in this study has four wheels and uses a continuous loop for trafficking by applying approximately 7,200 wheel loads per hour. This accelerated loading corresponds to typical highway traffic flow speeds. The wheels are pneumatic tires typically inflated to 690 kPa (100 psi) and are 12 in (300 mm) in diameter and 3.25 in (80 mm) wide, which is approximately one-third the diameter of standard truck tires. The loads applied to the scaled pavements structure or laboratory-prepared specimens can be varied from 430 lb (1.9 kN) to 610 lb (2.7 kN) by adjusting the height of the machine on top of the testing frame. The maximum linear speed at which the wheels travel during trafficking is about 6 mph, or 10 km/h (Rossmann et al., 2008).

Figure 1. Mobile Model Load Simulator (MMLS3) with Environmental Chamber Mounted (*left*)

During recent years, the third-scale load simulator has been used successfully for evaluating the performance of hot-mix asphalt pavements (Ebels et al., 2004; Epps et al., 2004; Hugo and Epps, 2004); testing various laboratory specimens (mostly slabs and briquettes) compacted to specific air void densities (Bhattacharjee et al., 2004; Lee et al., 2006a); and testing asphalt cores retrieved from the pavement (Lee, 2006b). There are several advantages of using this device for performance evaluation of thin wearing courses, including more realistic simulation of traffic loading; accurate temperature control when the special cover and/or environmental chamber is used; and the ability to evaluate other performance measures of the thin layers (e.g., fatigue, aggregate polishing, durability) (Im and Kim, 2012).

Sampling and Collection of Materials

In this study, loose samples of SM-9.5 dense-graded asphalt mixtures were collected from three VDOT districts: Bristol, Salem, and Lynchburg. SM-12.5D HR (HR designates a high RAP content) and the gap-graded or THMACO mixture were obtained from Superior Paving Corporation in Leesburg, Virginia, and the Fort Myer Construction plant in Washington, D.C., respectively. The SM-4.75 mixture was supplied by Lawhorne Brothers Paving in Lynchburg, Virginia. All sampled materials were plant-produced and designed in conformity with VDOT standard specifications and relevant special provisions (VDOT, 2010). Detailed information about the job-mix formulas and aggregate gradation for all the sampled materials is provided in Tables 1 and 2, respectively.

Full-Scale Pavement Section Testing

The SM-4.75 mixture was tested for rutting and fatigue by setting the MMLS3 directly on top of the paved test strip/lane at the ALF at TFHRC. The existing pavement was milled to an average depth of 28 mm (±4 mm), and then a tack coat was applied before the fine mixture was placed and compacted (Li et al., 2011). The device was set to apply 100,000 axle loads at 7,200 axles/hr, corresponding to a typical highway traffic speed. The 100,000 wheel passes is the minimum number of wheel passes established by the model load simulator users for acceptable rutting performance based on an empirical protocol (Rossmann et al., 2008). For the last 20,000 load applications, a slower speed (i.e., 7,000 wheels/hr) was used to simulate other more strenuous situations such as high truck volumes, ramps, and intersections.

For fatigue testing, the wander capability of the MMLS3 was employed to account for the lateral wander of the highway traffic. During testing, transversal profiles were measured after a predetermined number of axle loads. After each measurement of surface profiles, the testing was resumed as soon as the pavement surface had regained its prescribed temperature. Permanent deformation (rutting) testing was conducted at 64° C, and fatigue testing was conducted at 22° C (±2 °C). A heating/cooling unit (Figure 2) was used to control/monitor the temperature on the surface of the pavement during testing; a special cover made of polyvinyl material was placed over the machine and sealed at the bottom on the pavement to keep the temperature within the specified range. Hot air was circulated across the surface of the pavement using two 4-ft-long nozzles installed on each side of the machine and connected to the heating unit through flexible

Table 1. Job-Mix Formulas for Plant-Mixed Samples

Mixture Type	Mixture Phase (%)	Source	Location
SM-4.75D			
No. 9 Archmarble	10	Boxley Aggregates	Lynchburg, Va.
No. 10 Archmarble	60	Boxley Aggregates	Lynchburg, Va.
Processed RAP	30	Various stockpiles	Lynchburg, Va.
PG 64-22	6.2	Associated Asphalt Inc.	Roanoke, Va.
Adhere HP+ Additive	0.5	ARR-MAZ Products	Winter Haven, Fla.
SM-9.5A			
I 3's Diabase	30	Chantilly Crushed Stone	Chantilly, Va.
Crushed RAP	30	-	Various locations in N. Va.
Manufactured Sand	17	Chantilly Crushed Stone	Chantilly, Va.
Screening (Dust)	23	Chantilly Crushed Stone	Chantilly, Va.
PG 64-22	5.6	NuStar Asphalt	Dumfries, Va.
Kling Beta Additive	0.25	Akzo Nobel	Willowbrook, Ill.
SM-9.5D			
No. 8 Quartzite	42	Salem Stone	Sylvatus, Va.
No. 10 Quartzite Screening	13	Salem Stone	Sylvatus, Va.
Concrete Sand	20	Wythe Sand	Wytheville, Va.
Processed RAP	25	Adams Construction Co.	Roanoke, Va.
PG 64-22	5.7	Associated Asphalt Inc.	Roanoke, Va.
Adhere HP+ Additive	0.5	ARR-MAZ Products	Winter Haven, Fla.
SM-12.5D			
No. 78 Diabase	24	Luck Stone	Leesburg, Va.
No. 8 Diabase	13	Luck Stone	Leesburg, Va.
Natural Sand	12	Luck Stone	Caroline, Va.
Crushed RAP	26	Superior Paving	Leesburg, Va.
Manufactured Sand	25	Luck Stone	Leesburg, Va.
PG 64-22	5.2	NuStar Asphalt	Baltimore, Md.
Pavebond Lite	0.5	Rohm/Haas	Cincinnati, Ohio
THMACO			
No. 8 Diabase	72	Vulcan Materials	Warrenton, Va.
No. 10 Granite Screening	28	Vulcan Materials	Occoquan, Va.
PG 70-28	5.0	Bitumar USA Inc.	Baltimore, Md.
Adhere HP+ Additive	0.30	ARR-MAZ Products	Winter Haven, Fla.

RAP = recycled asphalt pavement.

ducts. Air was circulated in both directions when a swap switch was turned on so that both sides of the tested area received equal amounts of heat. The temperature was decreased during fatigue testing using the same setup. A temperature controller installed on the heating unit kept the temperature constant throughout both testing sessions (i.e., rutting and fatigue).

Laboratory-Prepared Slabs and Briquettes

For laboratory accelerated testing, 10 in by 12 in slabs with various thicknesses ranging from 1 in to 1.75 in (25 mm to 45 mm) were fabricated from the SM-9.5, SM-12.5, and THMACO mixtures using the linear kneading compactor (LKC) at TFHRC. With the LKC, only a fraction of the mixture is compacted at any given time. This kneading action allows the mixture to be compacted without excessive fracturing of the aggregate. Despite numerous attempts, the 7% to 8% air void target levels could not be achieved for the SM-9.5 and SM-12.5

Table 2. Aggregate Gradation for Dense- and Gap-Graded Mixtures

Sieve Size	% Passing	Tolerance ±%	Acceptance Range (Average of 8 Tests)	Design/Specification Range
SM-4.75D HR				
1/2 in	100	1	99-100	100
3/8 in	98	2.8	95.2-100.0	95-100
No. 4	91	2.8	88.2-93.8	90-100
No. 16	51	2.8	48.2-53.8	30-55
No. 200	10	0.7	9.3-10.7	6-13
VTM	5.0			
G_{mm}	2.487			
SM-9.5A HR				
1/2 in	100	1	99-100	100
3/8 in	91	2.8	88.2-93.8	90-100
No. 4	65	2.8	62.2-67.8	80 Max.
No. 8	38	2.8	35.2-40.8	38-67
No. 200	6.3	0.7	5.6-7.0	2-10
VTM	3.8			
G_{mm}	2.725			
SM-9.5D HR				
1/2 in	100	0	100	100
3/8 in	93	2.8	90.2-95.8	90-100
No. 4	59	2.8	56.2-61.8	80 Max.
No. 8	42	2.8	39.2-44.8	38-67
No. 200	5.8	0.7	5.1-6.5	2-10
VTM	3.5			
G_{mm}	2.468			
SM-12.5D HR				
3/4 in	100	0	100	100
1/2 in	91	2.8	93.2-98.8	95-100
3/8 in	65	2.8	85.2-90.8	90 Max.
No. 8	38	2.8	40.2-45.8	34-50
No. 200	6.3	0.7	4.5-5.9	2-10
VTM	3.8	-	-	-
G_{mm}	2.668	-	-	-
THMACO				
1/2 in	100	2	98-100	100
3/8 in	94	5	89-99	85-100
No. 4	38	4	34-42	25-40
No. 8	20	4	16-24	19-32
No. 16	15	3	12-18	15-23
No. 30	12	3	9-15	10-18
No. 50	10	3	7-13	8-13
No. 100	7	2	5-9	6-10
No. 200	6	1	5-7	4-7
VTM	No requirement	-	-	-
G_{mm}	2.468	-	-	-

VTM = Voids in Total Mix; G_{mm} = specific gravity of mix; Max. = maximum.

Figure 2. Testing for Rutting of SM-4.75 Mixture at Turner-Fairbank Highway Research Center. Cooling/heating unit pictured to right.

mixtures with the LKC. Density measurements indicated air void levels between 10% and 12%. With the use of a similar procedure, THMACO samples were compacted to 14% to 15% air void content. Rut testing was conducted in a specially designed frame (Figure 3) capable of accommodating four contiguous slabs with the aforementioned dimensions and thicknesses. The temperature was kept constant at 147° F (64° C) using the same setup as for the full-scale pavement section testing. The temperature of the bottom of the samples was generally around 142° F to 144° F (61° C to 62° C). All slabs were installed (glued) on top of a 0.5-in aluminum sheet, which was placed on a steel base plate to facilitate the rutting development. None of the specimens was tested for fatigue.

To compensate for the high air void contents of the SM-9.5 and SM-12.5 mixture slabs, briquettes 1.5 in and 1.75 in thick were prepared from gyratory-compacted specimens. For this purpose, specimens with a diameter of 7 in by 6 in were compacted to air void contents of about 7% in a gyratory compactor and then cut to the aforementioned thickness with a circular saw. Similar cylindrical samples with a diameter of 7 in by 6 in were prepared from the SM-4.75 mixture at 7% and 12% air void contents, and then 1-in-thick briquettes were cut from these samples. The 12% air void content for the specimens was similar to the air void content of the SM-4.75 mixture that was placed and compacted at the TFHRC ALF for comparison purposes. Three gyratory samples were prepared for each mixture.

Four additional SM-4.75 mixture specimens were compacted in the gyratory compactor at 1 in thickness. All briquettes were placed on ¼-in-thick aluminum plates before their installation in a specially constructed holder flush with the surface (Figure 4). The parallel sides of the briquettes were 4.25 in long.

(a)

(b)

Figure 3. Testing Frame: (a) untrafficked and (b) trafficked asphalt concrete specimens

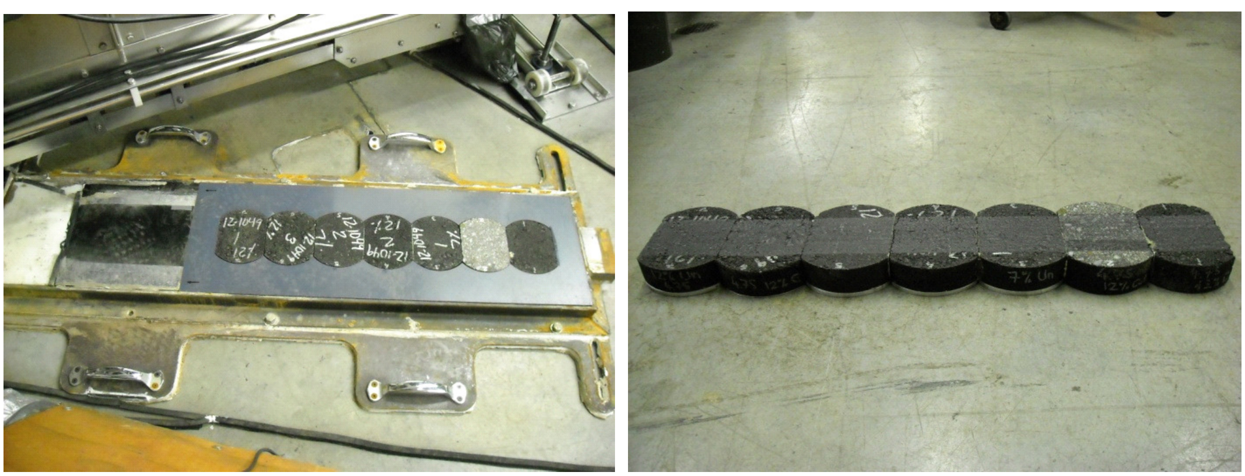


Figure 4. Set of Briquettes Installed in Testing Frame: before (*left*) and after (*right*) being tested under the MMLS3

RESULTS AND DISCUSSION

Overview

The rut depth results from the accelerated trafficking are summarized in Table 3. Test conditions were similar for the SM-4.75 mixture inlay at TFHRC and for all the specimens tested in the laboratory: a wheel load of 600 lb (272 kg), tire pressure of 100 psi (690 kPa), and loading rate of 7,200 axles/wheels per hour. No lateral wandering of the wheel was applied during rut testing.

Prior to the start of the tests, all specimens were conditioned to reach the predetermined, specified target temperature. Thermocouples installed at the bottom and on the surface of the specimens provided the actual temperatures at these locations. Except for the SM-4.75 mixture, all mixtures were tested only for rutting in the laboratory. Four slabs were compacted and tested from each 9.5 mm and 12.5 mm mixture (high air voids), whereas three briquettes were prepared and tested for the same mixtures (7% air voids). In addition, six briquettes, three for each air void content, were cut from the gyratory specimens made from the SM-4.75 mixture and compacted to air void contents of 7% and 12%. One briquette was cut from the middle of the 12% air voids gyratory pill in order to observe its performance during testing. Only three slabs were tested for the THMACO mixture. The slabs and briquettes prepared for testing had similar thicknesses, as presented in Table 3.

Tables 4 and 5 show the rutting progression data for all tested asphalt materials at up to 150,000 wheel load applications. It should be noted that in Table 5, rut depths at 7% air void content correspond to the briquettes cut from the top of the gyratory-compacted specimens. No briquettes were acquired from the bottom of the gyratory specimens. Cross-sectional profiles (rutting) measurements were taken with an electromechanical profilometer across the center of each slab and briquette at the wheel load intervals shown in the tables. In addition, zero-readings

Table 3. Laboratory and Field Rut Depths for Various VDOT Surface Mixtures

Mixture Type	Specimen Thickness, in (mm)	Binder	Aggregate Type	RAP (%)	Air Voids (%)	Axle Loads (thousand)	Rut Depth (mm)
SM-4.75 (TFHRC ALF)	1 (25)	PG 76-22	Diabase	20	13	100	3.57
SM-4.75 (Laboratory)	1 (25)	PG 64-22	Archmarble	30	6	150	0.67
					7		2.04
					10		0.72
					12		2.53
THMACO	1 (25)	PG 70-28	Diabase	None	15	100	2.47
SM-9.5A HR	1½ (40)	PG 64-22	Diabase	30	7	150	2.08
					11.5-12		8.31
SM-9.5D HR	1½ (40)	PG 64-22	Quartzite	25	7	150	2.74
					10.6-11.2		8.13
SM-12.5D HR	1¾ (45)	PG 64-22	Diabase	26	7	150	3.24
					10.5-11	100	18

RAP = recycled asphalt pavement; TFHRC ALF = Turner-Fairbank Highway Research Center Accelerated Loading Facility.

Table 4. Thin Mixtures Rutting Profile Measurement Progression (mm)

No. Wheel Loads	SM-4.75 TFHRC ALF Air Voids 13%	SM-4.75D Laboratory Air Voids 7%[a]	12%[a]	6%[b]	10%[b]	THMACO Air Voids 15%
5,000	0.848	0.453	0.187	0.066	0.112	0.533
10,000	1.275	0.664	0.325	0.172	0.231	0.816
25,000	1.953	1.028	1.066	0.293	0.363	1.275
50,000	2.792	1.354	1.534	0.374	0.475	1.873
75,000	3.303	1.635	2.322	0.466	0.623	2.311
100,000	3.576	1.826	2.411	0.528	0.677	2.475
150,000	-	2.048	2.534	0.673	0.725	-

TFHRC ALF = Turner-Fairbank Highway Research Center Accelerated Loading Facility.
[a] Briquettes were cut to 1 in thick from 7-in-tall gyratory cylinders.
[b] Briquettes were compacted to 1 in thick.

Table 5. Regular Mixtures Rutting Profile Measurement Progression (mm)

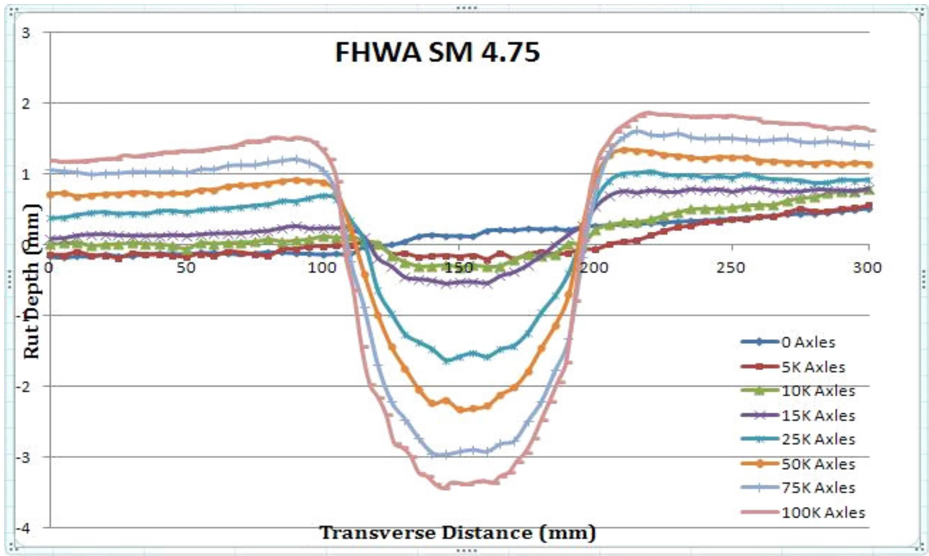
No. Wheel Loads	SM-9.5A HR Air Voids 7%	12%	SM-9.5D HR Air Voids 7%	11%	SM-12.5D HR Air Voids 7%	11%
5,000	0.564	1.016	0.364	1.017	0.427	0.508
10,000	1.126	1.524	0.646	1.524	0.886	1.272
25,000	1.383	2.541	1.128	2.542	1.453	3.302
50,000	1.758	4.064	1.785	3.814	1.985	5.334
75,000	1.823	5.084	2.283	4.826	2.496	15.241
100,000	1.917	6.096	2.566	6.096	2.877	17.761
150,000	2.088	8.313	2.736	8.127	3.246	-

(i.e., no loads applied) were taken so that all subsequent measured profiles could be normalized and the permanent deformation development could be accurately monitored over the testing course. Prior to the taking of the zero-readings, 100 wheel loads were applied to ensure proper seating of the specimens as per the MMLS protocol (Rossmann et al., 2008). All profile readings corresponding to tested specimens from the same mixture were averaged.

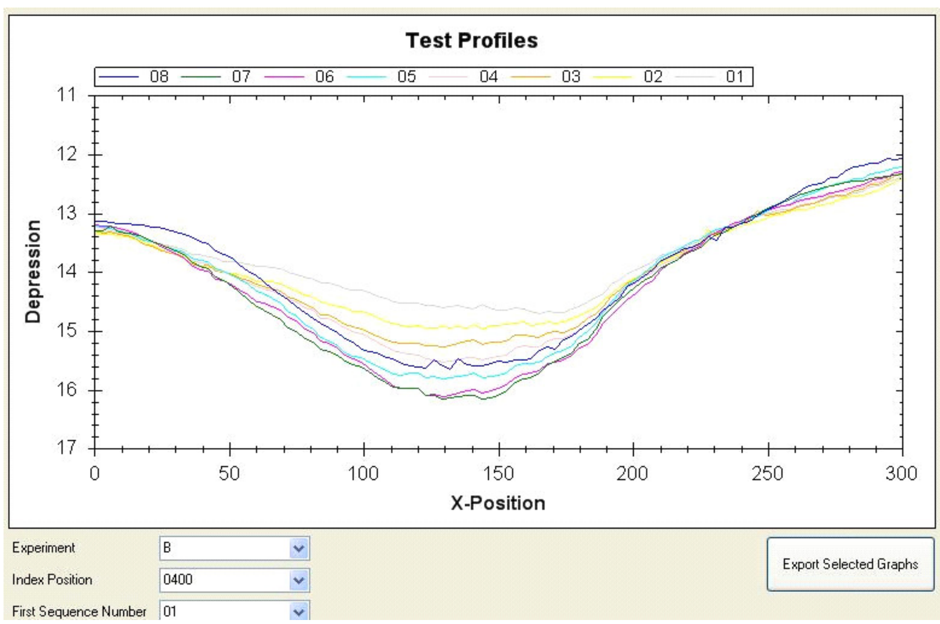
"Down" rutting readings were defined and measured as the depth of the rut measured from the original surface profile across the imprint of the pneumatic tire into the surface of the specimen. In addition, the rutting profiles were normalized (i.e., shifted upward to the x-axis) for more accurate comparisons. An example of this procedure is shown in Figure 5a for the field section (i.e., placed at TFHRC) of the SM-4.75 mixture. Figure 5b shows the rutting development during fatigue testing of the same mixture. In this figure, the fatigue raw data are presented before being normalized with respect to the x-axis. The average cumulative rutting for all the mixtures is illustrated in Figures 6 and 7.

Rutting Results for SM-4.75 and THMACO Mixtures

For the SM-4.75 mixture, similar laboratory rutting results were obtained for specimens compacted to 7% and 12% air voids in the gyratory compactor, as can be seen in Figure 6. These samples were cut to 1 in (25 mm) from the top of the 7-in-tall specimens. Slight rutting (less than 1 mm) was observed in the specimens compacted to 1 in even though two of them had about 10% air voids (Figure 7). A reason these specimens showed less rutting could be related to



(a)



(b)

Figure 5. Rutting Development for SM-4.75 Mixture at Turner-Fairbank Highway Research Center (FHWA): (a) Rutting, No Wander (normalized data); (b) Fatigue, With Wander (less rutting)

binder stiffening attributable to reheating of the material. Another reason may stem from the aggregate orientation and interlocking (anisotropy of the specimen) as these two aspects are different between the cutout specimens and the compacted specimens. Button et al. (1994) and Masad et al. (1999) established that aggregates in thinner compacted specimens have a preferred horizontal orientation whereas thicker specimens display a random particle distribution, thus allowing for further vertical movement within the specimen. In addition, Wang et al. (2001) discovered that pavement-cored specimens had larger air void contents at the bottom than at the top, indicating a decreased compaction effect in this area. Similar rutting (2.526 mm) was observed in the specimen cut from the middle of the 12% air voids pill as compared to the ones cut from the top.

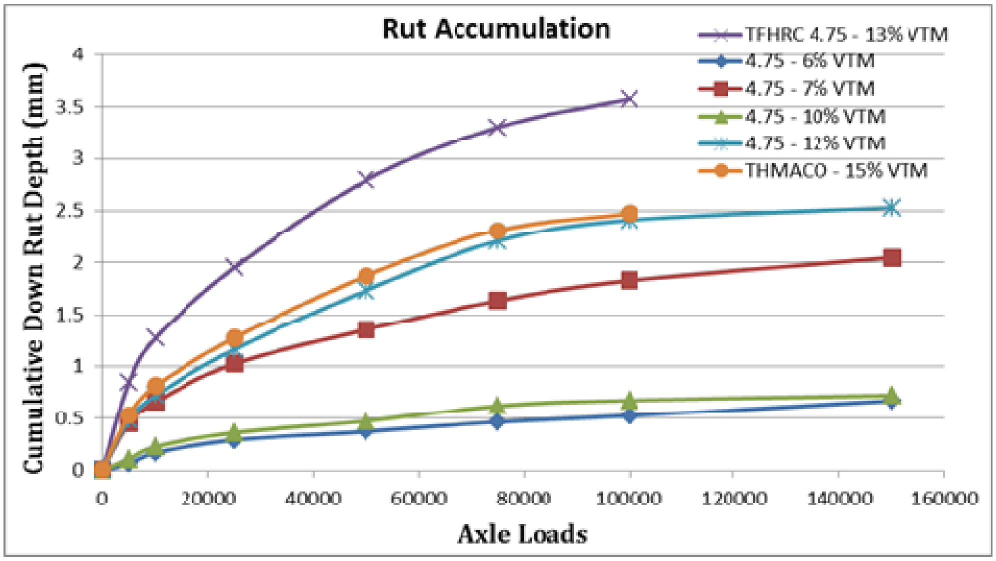


Figure 6. Average Cumulative Rutting for Thin Mixtures at 147° F (64° C)

(a) (b)

Figure 7. Rutting Profiles of SM-4.75 Mixtures: (a) specimens cut from 7-in-tall cylinders, and (b) specimens compacted to 1 in

Higher rutting depths were acquired for the SM-4.75 mixture inlay at TFHRC because of increased air void contents (approximately 13%). In this case, cores taken from the pavement have provided air void contents ranging from 10.4% to 13.2%. In addition, this mixture had a stiffer unmodified binder (PG 70-22) than the control binder and incorporated 20% RAP, 10% less than the mixture used for laboratory testing. It was placed on top of a crushed aggregate base course with the total thickness of the hot-mix asphalt layer being 5.8 in (150 mm). Likewise, laboratory results (e.g., flow number, dynamic modulus, and Hamburg test) indicated high rutting susceptibility attributable to the high air void content. Nonetheless, the full-scale testing was considered acceptable for this thin mixture as the induced multiaxial compressive stresses were not a great contributor to rutting compared to the shear stresses in a thicker pavement layer (Li et al., 2011).

By comparison, much larger rut depths of about 14 mm were obtained under the ALF at TFHRC for this mixture after 25,000 wheel loads (Nelson et al., 2011). Testing was also conducted at 147° F (64° C) with the wheel load and tire pressure used for rutting being 10,000 lb (44 kN) and 100 psi (690 kPa), respectively. Comparable rutting depths of approximately 4.6 mm after 150,000 wheel passes were acquired only during rutting testing at a lower temperature (i.e., 45 °C) or during fatigue testing, when lateral wheel wander was applied. Similar initial stage (up to 15,000 load passes) rut progression tendencies were observed after testing with the MMLS3 compared to the full-scale testing, pointing to the fact that data from the laboratory can be used to predict actual pavement performance under certain conditions.

In addition, the gap-graded THMACO showed excellent rutting resistance although the air void content was around 15%. Typically, for thin mixtures (i.e., up to 1½ in), rut depths of 2.7 mm or less are considered adequate at 100,000 wheel load applications as per the MMLS3 protocol guidelines (Rossmann et al., 2008). However, for the THMACO, there are no in-place air void requirements for compaction as its strength is provided mostly by the stone-on-stone contact. One of the three tested specimens exhibited slightly higher heave (about ¼ in) on the sides (Figure 8, *right*).

A likely reason for this heaving could be poor compaction in the LKC on the specimen edges. Earlier experience with the THMACO mixture has proved beneficial for some pavement sections, with sites such as S.R. 164 in Suffolk, Virginia (Tate and Clark, 2004), and I-66 near Fairfax, Virginia (R. Seale, personal communication, 2012), showing adequate performance over the years. Applications of the mixture in these two cases were 5/8 in (16 mm) thick.

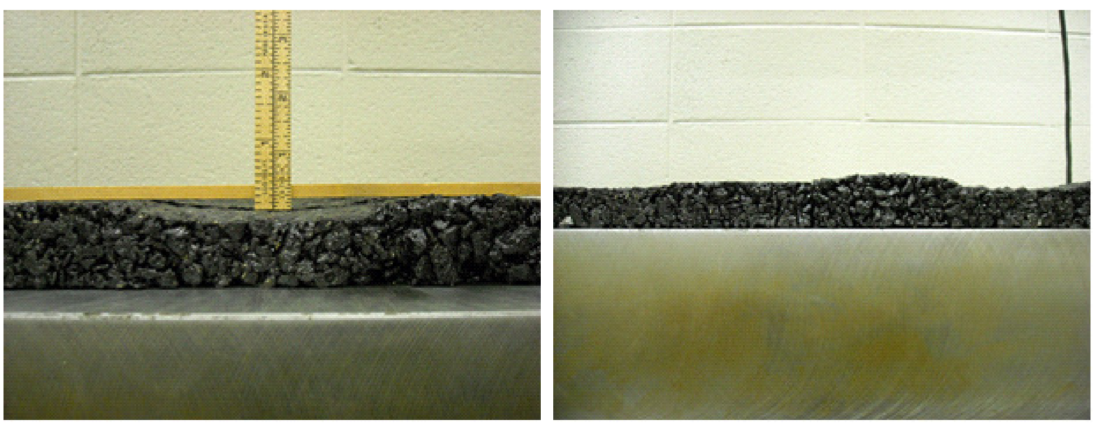


Figure 8. Rutting Profile of THMACO Mixture Tested in Laboratory at 147° F (64° C). The photograph to the *right* shows about ¼ in heaving on the sides.

Rutting Results for SM-9.5 and SM-12.5 Mixtures

These conventional mixtures exhibited similar trends in rutting as compared to the thin mixtures at 7% air void contents as shown in Figure 9. Similarly, large rut depths of about 8 mm for the SM-9.5 mixtures and 18 mm for the SM-12.5D mixture were reached after 150,000 wheel passes for specimens compacted to air void contents of approximately 10% and higher. Testing was stopped after 100,000 wheel load applications for the SM-12.5D mixture as debonding and excessive heaving were noticed within the specimens, as illustrated in Figure 10. In addition, deep ruts formed within the slabs, as depicted in Figure 11.

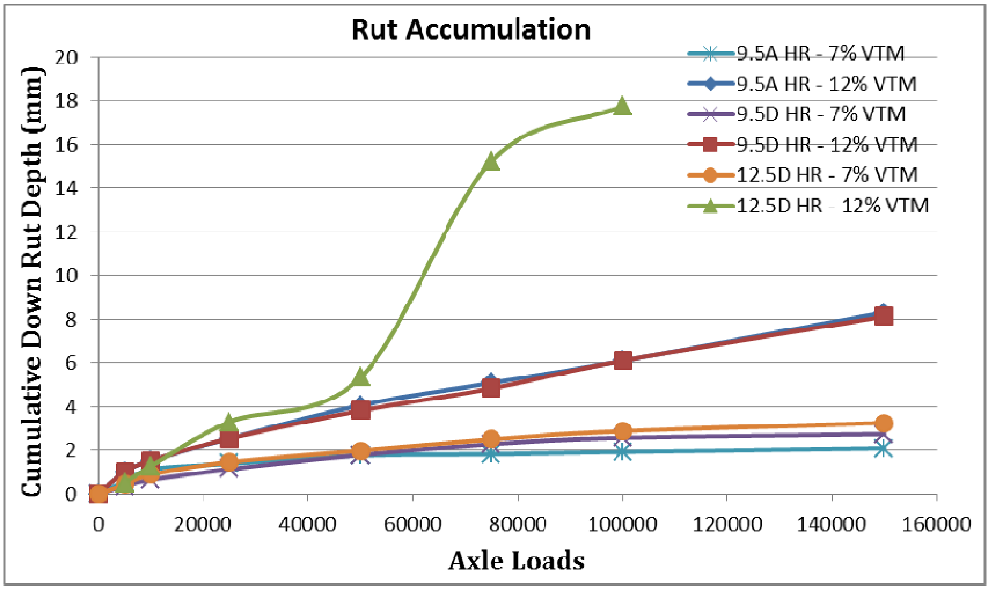


Figure 9. Average Cumulative Rutting for Conventional Mixtures

Figure 10. Debonding and Heaving in SM-12.5D HR Mixture During Rutting Tests at 147° F (64° C)

Figure 11. Difference in Rutting Between SM-9.5A HR (*left*) and SM-12.5D HR (*right*) Mixtures. Excessive heaving can be observed in the SM-12.5D mixture

The “sudden” jump in rutting after 55,000 wheel passes exhibited by the SM-12.5D mixture with high RAP content (26%) could be due to low asphalt binder content in the mixture (virgin and RAP) or insufficient compaction, leading to a high air void content, in the LKC. These assumptions are supported by the fact that the sides of all four tested slabs showed signs of coarse aggregate debonding leading to excessive heave (atypical rise in the sides of the slab because of the large crack development) and rutting compared to the SM-9.5 mixtures (Figure 11). However, this behavior was not observed in the smaller specimens (briquettes) compacted to 7% air void content and tested at the same temperature, as shown in Figure 12. As seen in this figure, two of the specimens (cut from the top of the gyratory pill) were placed upside down in the frame to observe for any “unusual” deformation during the accelerated loading. No atypical deformation (e.g., too much or too little rutting) was observed in these specimens during testing.

Slight qualitative variations in rutting were observed between the two SM-9.5 mixtures although the total down rut was practically the same. This could be due to dissimilar air void percentages and/or RAP contents for each mixture. No shoving, raveling, or cracking was observed in any of the tested specimens after applications of 100,000 or 150,000 axle loads.

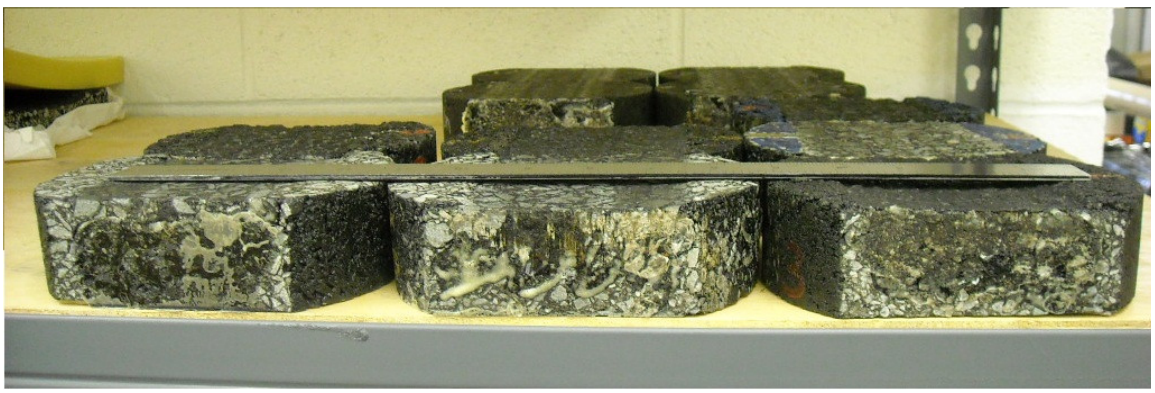


Figure 12. Rut Depths of SM-9.5A (*far left*), SM-9.5D (*middle*), and SM-12.5D (*right*) Mixtures at 147° F (64° C)

Comparisons to Results of Other States With Regard to Thin Mixtures

Rut depths of approximately 15 mm at 11.7% air voids and 5 mm at 8.3% air voids were observed in a 9.5 mm Superpave surface mixture used by the North Carolina Department of Transportation tested under the same loading and laboratory conditions as those discussed earlier, but at a lower temperature (40° C) (Lee et al., 2006b). For this testing, the 1½-in-thick slab was placed on a 6-in-thick softer material (neoprene). Similar work was conducted by Mallick et al. (2005) on three different surface mixtures using granite and traprock as aggregate and PG 76-28 as the asphalt binder at 140° F (60° C). In this study, the rut depths in the 1½-in slabs were in the 2.3 mm to 3.8 mm range after 80,000 wheel load applications for mixtures having air void contents between 6% and 8%. In both cases, the slabs were compacted in a special mold in the laboratory using a walk-behind roller compactor.

Regarding field testing using the MMLS3, Smit et al. (2003) and Epps et al. (2003) conducted accelerated trafficking on several sections at NCAT and on U.S. 281 in Jacksboro, Texas, respectively. During both studies, testing was performed on nine different 12.5 mm mixtures at a surface temperature of 122° F (50° C). Most of the tested mixtures were impermeable, with air voids ranging from 6.8% to 8.5%. In these cases, the rut depth measurements after 100,000 and 160,000 load repetitions indicated values ranging from 2.2 mm to 3.5 mm for NCAT sections with 3-in-thick surface layers; values of 1.4 mm to 4.8 mm were observed for the Texas pavement structure having 4-in-thick surfacing layers. These results, which were obtained under less harsh test conditions than those of the VDOT thin mixtures (i.e., SM-4.75, THMACO, etc.), indicate that the VDOT thin mixtures tested in this study provided better rutting performance.

Given the limited full-scale and the field/laboratory scaled accelerated testing of these thin preservation alternatives, it is premature to rank their permanent deformation performance with confidence. Other studies conducted on scaled pavement structures indicated that the rutting results after the application of 100,000 MMLS3 axles provide a good indication of the ultimate rutting performance of the pavement when the results are extrapolated to a number of critical load applications that are anticipated during the life cycle of the pavement (Kim et al., 1998). For applications where the risk of failure is required to be very low, the test should be extended to 200,000 or more wheel loads. This will reduce the margin of error in the final prediction of rutting (Rossmann et al., 2008). It is also important to select the performance prediction methodologies carefully because of the differences that exist between field conditions and laboratory testing conditions.

CONCLUSIONS

- *The MMLS3 is capable of providing a means to assess the relative performance of the thin wearing courses (meet pass/fail criteria) as well as the conventional mixtures.*

- *Based on the data collected for all mixtures that were tested under identical conditions in the laboratory, the SM-4.75 mixture has the best rutting performance (i.e., lowest rut depths), followed by the SM-9.5A, THMACO, SM-9.5D, and SM-12.5D mixture. Further, the briquettes compacted to 1 in from the SM-4.75 mixture have the least permanent deformation among all the specimens because of a better densification of the material in the compactor given the lesser amount of material being compacted.*

- *THMACO performs well, both in the laboratory and field, particularly considering its thin lift placement and no requirement for in-place density.*

- *Rut depths for all the mixtures with air void contents between 6% and 8% are less than or equal to the limits established by the protocol guidelines developed for rut testing (Rossmann et al., 2008), with slight differences among the mixtures.*

- *Specimens cut from the top of the gyratory-compacted pills rut more than those that are originally prepared as thin specimens. This could be due to the air void distribution in the specimen or a certain orientation of the aggregates that would allow for further densification.*

- *The VDOT thin and conventional-thickness dense- and gap-graded mixtures that were examined in this study hold up better than other similar mixtures used by other states, especially given that testing conditions were harsher in the Virginia tests (e.g., higher temperatures, stiffer underlying material, higher number of load repetitions).*

- *Additional field and laboratory testing is needed to account for various mixture and placement characteristics (e.g., thickness/density of the surface layer, compaction method, amount of RAP incorporated, specimen preparation, etc.) and their effects on rutting performance.*

RECOMMENDATIONS

1. *Based on its field and laboratory rutting performance, VDOT's Materials Division should encourage the use of the SM-4.75 mixture on low- to medium-traffic roadways and for maintenance and/or preservation applications. Further, with regard to its field installation, additional passes of the roller should be applied to achieve in-place air voids of approximately 10%.*

2. *VDOT's Materials Division and VCTIR's asphalt and pavement researchers should use the accelerated trafficking methods applied through this study to assess better the stability of the experimental mixtures before field placement.*

3. *Virginia Tech should conduct additional tests to account for unexpected differences in rutting performance in specimens obtained from the middle and bottom of a gyratory sample so that a robust protocol for sample preparation and testing can be established. In addition, slabs with levels of air voids similar to those of the gyratory briquettes should be prepared so that rut comparisons can be performed.*

4. *Virginia Tech in concert with VCTIR and VDOT's Materials Division should work closely with several contractors so that various thin wearing courses of interest or known performance could be placed at the Virginia Smart Road and/or at the contractor's yard, if technically practical, for accelerated testing.* It is anticipated that this type of testing will render valuable input to VDOT materials and pavement engineers and to managers with respect to the final mixture selection.

BENEFITS AND IMPLEMENTATION PROSPECTS

The findings of this study support the use of SM-4.75 materials as thin overlays for low- to medium-traffic roadways and for maintenance/preservation applications. The ability of the SM-4.75 mixtures to make effective use of less expensive aggregate source material creates an economical alternative for municipalities and higher volume commercial users. This expanded market, combined with the lower raw materials costs, likewise represents a significant opportunity for aggregate suppliers and AC producers.

The benefits of the accelerated trafficking system or MMLS3 include portability, application of realistic rolling wheel contact stresses (including a wandering mode), and temperature and speed control, both indoors and outdoors. Hence, the use of the scaled accelerated loading facility allows a cost-effective response to many inquiries regarding pavement and materials behavior and performance. In terms of practical examples, inquiries that can be addressed include identification and highlighting of deficiencies in current practices, variability of materials and layer properties, improved understanding of the relationships between the laboratory and field behavior of various materials, and the effects of various real environmental conditions and construction standards on pavement behavior and performance.

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