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# Evaluation of the MMLS3 for Accelerated Wearing of Asphalt Pavement Mixtures Containing Carbonate Aggregates

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**VIRGINIA CENTER FOR TRANSPORTATION INNOVATION AND RESEARCH**

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<p>16. Abstract:</p> <p>The purpose of this study was to develop an accelerated wearing protocol for assessing the susceptibility of asphalt surface mixtures to polishing. This was the second phase of the study. The first phase focused on assessing the characteristics of selected carbonate aggregates available in Virginia that are normally classified as "polishing" and thus not considered suitable for use in pavements except for those roads with an average daily traffic of less than 750 vehicles per day. The selection of aggregates used in pavements is critical in producing surfaces that will continue to provide good skid resistance through a lengthy service life. The specifications of the Virginia Department of Transportation (VDOT) call for "non-polishing aggregate" for use in most surface layers. The study was aimed at making use of locally available polishing aggregates that can reduce the cost of asphalt mixtures while maintaining satisfactory wearing and skid characteristics of the pavements.</p> <p>The objectives of the research were (1) to evaluate the polishing/wear features of mixtures containing limestone aggregate in the laboratory using an accelerated method; (2) to compare friction properties of the laboratory-polished specimens with actual pavement friction measurements; and (3) to compare friction properties of mixtures containing carbonate rock or blends with those of mixtures with non-carbonate rocks. The study included three types of aggregates, i.e., limestone, quartzite, and granite, and blends of these aggregates. The surface mixtures studied were conventional SM-9.5 and SM-12.5 mixtures containing various percentages of limestone, limestone recycled asphalt pavement, and limestone-granite/quartzite blends.</p> <p>The suggested test protocol to evaluate the polishing of asphalt concrete specimens prepared in the laboratory was developed using the third-scale model mobile load simulator (MMLS3). The MMLS3 is capable of applying realistic rolling wheel contact stresses similar to those on highways from the moving traffic.</p> <p>The skid resistance, friction, and texture of actual pavement surfaces and laboratory-fabricated specimens were measured after different polishing intervals. Skid resistance and frictional characteristics were measured by the British pendulum tester, dynamic friction tester, and locked-wheel skid tester; the circular texture meter was used to measure surface macrotexture. Results showed that the MMLS3 can be used to simulate traffic wearing of asphalt concrete specimens of different shapes and sizes in the laboratory including core specimens removed from existing pavements and that the BPT is effective in characterizing changes in friction on specimens that are subjected to simulated trafficking via the MMLS3. Further, test specimens should have a high initial macrotexture and mixtures should have good stability so that the wearing effects are focused on the aggregates. The study recommends that the Virginia Center for Transportation Innovation and Research (VCTIR) work with Virginia Tech and VDOT's western districts to design and conduct an experiment to explore a series of carbonate / non-carbonate aggregate blends for asphalt mixtures and that the mixture gradations be designed to prevent the absence of macrotexture from impacting the ability to measure the "polish" of the coarse aggregate structure of the experimental mixtures. VCTIR should purchase tires with different tread patterns and try them on the MMLS3 to evaluate the polishing rate of specimens in more detail.</p>			
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**FINAL REPORT**

**EVALUATION OF THE MMLS3 FOR ACCELERATED WEARING OF ASPHALT  
PAVEMENT MIXTURES CONTAINING CARBONATE AGGREGATES**

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## ABSTRACT

The purpose of this study was to develop an accelerated wearing protocol for assessing the susceptibility of asphalt surface mixtures to polishing. This was the second phase of the study. The first phase focused on assessing the characteristics of selected carbonate aggregates available in Virginia that are normally classified as “polishing” and thus not considered suitable for use in pavements except for those roads with an average daily traffic of less than 750 vehicles per day. The selection of aggregates used in pavements is critical in producing surfaces that will continue to provide good skid resistance through a lengthy service life. The specifications of the Virginia Department of Transportation (VDOT) call for “non-polishing aggregate” for use in most surface layers. The study was aimed at making use of locally available polishing aggregates that can reduce the cost of asphalt mixtures while maintaining satisfactory wearing and skid characteristics of the pavements.

The objectives of the research were (1) to evaluate the polishing/wear features of mixtures containing limestone aggregate in the laboratory using an accelerated method; (2) to compare friction properties of the laboratory-polished specimens with actual pavement friction measurements; and (3) to compare friction properties of mixtures containing carbonate rock or blends with those of mixtures with non-carbonate rocks. The study included three types of aggregates, i.e., limestone, quartzite, and granite, and blends of these aggregates. The surface mixtures studied were conventional SM-9.5 and SM-12.5 mixtures containing various percentages of limestone, limestone recycled asphalt pavement, and limestone-granite/quartzite blends.

The suggested test protocol to evaluate the polishing of asphalt concrete specimens prepared in the laboratory was developed using the third-scale model mobile load simulator (MMLS3). The MMLS3 is capable of applying realistic rolling wheel contact stresses similar to those on highways from the moving traffic.

The skid resistance, friction, and texture of actual pavement surfaces and laboratory-fabricated specimens were measured after different polishing intervals. Skid resistance and frictional characteristics were measured by the British pendulum tester, dynamic friction tester, and locked-wheel skid tester; the circular texture meter was used to measure surface macrotexture. Results showed that the MMLS3 can be used to simulate traffic wearing of asphalt concrete specimens of different shapes and sizes in the laboratory including core specimens removed from existing pavements and that the BPT is effective in characterizing changes in friction on specimens that are subjected to simulated trafficking via the MMLS3. Further, test specimens should have a high initial macrotexture and mixtures should have good stability so that the wearing effects are focused on the aggregates. The study recommends that the Virginia Center for Transportation Innovation and Research (VCTIR) work with Virginia Tech and VDOT’s western districts to design and conduct an experiment to explore a series of carbonate / non-carbonate aggregate blends for asphalt mixtures and that the mixture gradations be designed to prevent the absence of macrotexture from impacting the ability to measure the “polish” of the coarse aggregate structure of the experimental mixtures. VCTIR should purchase tires with different tread patterns and try them on the MMLS3 to evaluate the polishing rate of specimens in more detail.

## **FINAL REPORT**

### **EVALUATION OF THE MMLS3 FOR ACCELERATED WEARING OF ASPHALT PAVEMENT MIXTURES CONTAINING CARBONATE AGGREGATES**

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## **INTRODUCTION**

Highway safety, as is strongly related to pavement friction (also referred to as skid resistance), has become of paramount importance both nationally and internationally (American Association of State Highway and Transportation Officials [AASHTO], 1976 ; Hall et al., 2009; Henry, 2000; Izeppi et al., 2010). Recent studies have indicated a high correlation between wet pavements with low skid resistance and accident rates (Flintsch et al., 2002; Flintsch et al., 2003; Kowalski et al., 2010; Masad et al., 2009), with the latter being almost double in wet weather. This leads to an annual average of about 6 million crashes, approximately 40,000 fatalities, and 3 million injuries, costing the U.S. economy more than \$200 billion (Habib, 2009). Typically, fine and coarse aggregates in combination with a type of binder (e.g., cement or asphalt) represent the main components of a pavement surface layer. This combination provides the surface texture of the pavement, which is the main factor affecting its friction. The consensus is that the surface texture is characterized by two main components: microtexture and macrotexture. For asphalt pavements, microtexture is a function of the aggregate surface irregularities (or microasperities) and macrotexture is a function of the coarse aggregate arrangement in the pavement surface.

In the last decade, the Federal Highway Administration (FHWA) and AASHTO have initiated and conducted a series of highway safety improvement programs and research studies aimed at reducing the number of fatalities and serious injuries arising from vehicle crashes (Habib, 2009; Hall et al., 2009; Shaffer et al., 2006). This objective can be achieved only through better friction management of existing pavements and better design practices of new pavement surfaces leading to long-term adequate friction. However, a 3-year study by Jayawickrama et al. (1996) pointed out that friction design methods of almost one-half of the states (21 of 48) do not consider any guidelines when addressing pavement skid resistance. For the other half, even though various guidelines are applied, methods may vary.

The Virginia Department of Transportation's (VDOT's) Wet Accident Reduction Program, which was started in the early 1970s, is also an important component of the FHWA safety program. The main focus of VDOT's program was to reduce highway fatalities by improving pavement friction characteristics at identified locations with a high incidence of "wet accidents." Successive friction testing at these "hotspots" allowed VDOT districts to take the necessary measures to improve the pavement surface properties on the roadway sections that might not offer adequate friction during wet conditions.

To provide adequate friction on asphalt pavements, polish-resistant coarse aggregates should be used in most of the surfaces (AASHTO, 1976; Mahone and Sherwood, 1995; Webb, 1970). These tend to retain their microtexture through their hardness (mineralogy), texture and fabric, and resistance to polishing and wear from vehicle tires. Therefore, to maintain a high level of wet pavement surface friction (or skid resistance), aggregates should not wear uniformly; that is, they should not become rounded or polished because of traffic. Because the rate of aggregate polishing is closely related to the types of minerals they contain, a high percentage of hard and well-bonded mineral grains must be present in the aggregates. For concrete pavements, the cement paste and fine aggregate provide good surface friction, as the coarse aggregates are not exposed to traffic (Hall et al., 2009).

Regarding polishing of aggregates, VDOT specifications (VDOT, 2007) call for "non-polishing aggregate" for use in most surface layers unless the traffic is less than 750 vehicles per day for a two-way road. However, VDOT materials engineers have few methods or tools with which to assess the polishing characteristics of aggregates to distinguish between polishing and non-polishing aggregates. This is primarily a problem in the western part of Virginia where the predominant source materials for aggregates are carbonate rocks (e.g., limestone) and are thus considered to be polishing aggregates. This situation often necessitates lengthy transport of non-polishing aggregate for use in surface layer construction at a time when transportation costs, both in economic and environmental terms, have skyrocketed.

## **PURPOSE AND SCOPE**

The purpose of this study was to develop an accelerated wearing protocol for assessing the susceptibility of asphalt surface mixtures to polishing. To achieve this objective, several asphalt concrete mixtures containing various amounts of carbonate aggregate, mostly limestone, and recycled asphalt pavement (RAP) were obtained from VDOT's Bristol District. Testing was conducted on slabs compacted in the laboratory and specimens cored from the pavement using an accelerated trafficking machine. The assessment of the surface mixtures containing various amounts of carbonate aggregate as coarse and fine aggregate will help to refine guidelines regarding the use of carbonate aggregate while maintaining satisfactory wearing and skid characteristics of the pavements.

## **METHODS**

### **Background**

#### **Pavement Surface Characteristics**

Pavement friction design, as part of flexible or rigid pavement design, has become increasingly important over the years because of highway safety related issues (Hall et al., 2009; Mahone and Sherwood, 1995; Mahmoud and Masad, 2007; Stroup-Gardiner et al., 2004). To obtain both initial and long-term friction for a pavement surface, whether asphalt or concrete, proper identification of the materials and construction methods that will provide adequate surface microtexture and macrotexture is required. On the whole, pavement surface texture is influenced by factors such as aggregate texture, aggregate gradation, pavement finishing methods, and degree of wear. The friction of an asphalt pavement friction surface is a time-dependent characteristic. Usually, this increases within a period of 2 years after mixture placement as the asphalt binder gets removed by traffic and the aggregate surfaces become exposed. After this period, the pavement starts to lose friction because of the polishing of the coarse/fine aggregate and prolonged wearing of its texture and ultimately reaches a condition referred to as “terminal polish” (Anderson et al., 1986; Skerritt, 1993).

However, surface microtexture and macrotexture influence the pavement skid resistance differently, but they both affect the tire-pavement interaction (friction). Hence, skid resistance is a combination of the effects of these two types of textures as they provide the optimal conditions to prevent vehicle tires from sliding on the pavement surface instead of rotating. This interaction is governed by three key mechanisms: (1) adhesion, which is the small-scale interaction between the tire and pavement aggregate surfaces; (2) hysteresis, which is governed by bulk deformation of the tire when squeezed against the pavement surface; and (3) pavement surface drainage, which is related to aggregate gradation and finish quality of the pavement surface (macrotexture). Drainage is largely influenced by the macrotexture, as it provides escape routes for water at the tire-pavement interface, thus reducing the potential for vehicle hydroplaning (Hall et al., 2009; Henry, 2000; Mahone and Sherwood, 1995; Shaffer et al., 2006). Generally, the microtexture affects the adhesion component of the pavement-tire friction as more direct contact exists between the tire and the aggregate (mostly coarse) surface. It is the microtexture that controls the friction, wet and dry, at low speeds. On the other hand, the hysteresis is mainly affected by the macrotexture because of bulk deformation of the tire when in contact with the pavement. This characteristic has a large impact on the friction at higher speeds, usually over 30 mph.

#### **Effect of Aggregates on Pavement Friction / Skid Resistance**

Aggregate rock type (e.g., basalt, diabase, granite, carbonate, etc.) has an impact on the pavement friction (Mahone and Sherwood, 1995, Mahone and Sherwood, 1996; Masad et al., 2009; Webb, 1970). Major issues regarding aggregates are the rate and manner in which they wear when subjected to repeated trafficking. Softer minerals (e.g. calcite) wear readily, and thus relatively pure limestone tends to wear quickly under traffic to present a smooth (“polished”)

surface texture with a low microtexture. Dolomite, the other major carbonate mineral, is harder than calcite and thus wears more slowly.

Early VDOT research suggested that the limestones and dolomites supplied from the western part of the state were generally polish susceptible (Mahone and Sherwood, 1995, 1996; Webb, 1970). The acid insoluble residue test indicates the non-carbonate fraction of the rock, providing a first-cut estimation of its polish susceptibility. Higher amounts of insoluble minerals in the aggregate at the surface layer will exhibit dissimilar wearing characteristics (Barksdale, 1991), thus continually providing a rough surface with good friction. The size and nature of the insoluble materials as well as the dolomite-calcite ratio also impact polish susceptibility. Silt or sand-sized quartz that is well disseminated through the rock offers better polish resistance than an equal amount of insoluble material composed of clay minerals. Limestone aggregates that are composed primarily of fine-grained calcite and are texturally homogeneous wear and polish relatively quickly even under moderate traffic volumes, thus leading to rapid loss of pavement friction. Dolomite is harder than calcite, and thus dolomitic rocks are more wear resistant than limestones, and rocks composed of mixtures of dolomite and calcite will tend to wear differentially and maintain a rough surface. In contrast to carbonates, harder rocks such as granite or basalt composed of much harder minerals require much higher traffic volumes to wear and polish hence providing wet skid resistance properties for a longer time before critical pavement slipperiness occurs.

To reduce the need for costly importation of non-polishing aggregate to construct skid-resistant asphalt pavement surfaces, VDOT has also tried blending small amounts of non-polishing aggregate with larger amounts of polishing aggregate (e.g., limestone). To achieve this goal, blends of these materials, i.e., 30% non-polishing coarse aggregate (greenstone and gravel) and 70% polishing aggregate (limestone), were placed at five experimental sites: three in the Bristol District and two in the Staunton District (Hughes and Mahone, 1975, 1979). The sites were monitored for 4 years and it was concluded that they performed very well under relatively high traffic volumes. Improved skid resistance has also been achieved by using limestone screenings in surface mixtures in some western parts of Virginia, although the procedure has created durability issues on these surfaces (Maupin, 1982). Unfortunately, there was little follow-up in succeeding years since transportation costs at that time were not a driving issue.

### **Methods for Assessing Polishing of Asphalt Mixtures**

In recent years, many devices have been used to polish various aggregates and asphalt mixture specimens, but none was actually adopted for day-by-day operations for a variety of reasons (e.g., testing too small of an area or time-consuming and unreliable). Comparisons of accelerated polishing methods can be found elsewhere (e.g., Masad et al., 2009; Kowalski et al., 2010). Currently, only two devices are used for accelerated polishing of aggregates and mixtures: (1) the British wheel (ASTM D3319) used for polishing coarse aggregate coupons and (2) the recently developed NCAT (National Center for Asphalt Testing) polishing machine used for polishing asphalt concrete slabs. Testing using these devices is followed in most of the cases by friction measurements with devices presented in the following section. A short description of the two devices is given here.

### *Accelerated Polishing of Aggregates Using the British Wheel (AASHTO T 279, ASTM D3319)*

This test method simulates the polishing action of vehicular traffic on coarse aggregates used in pavements. The polished value is a measure of the accelerated polishing caused by a British wheel followed by a friction test using the British pendulum tester (BPT) (ASTM E303). The obtained friction values are used to rate or classify coarse aggregates for their ability to resist polishing under traffic. The method cannot be used on asphalt or concrete mixtures. After the polishing action is completed, the specimens or coupons are removed from the fixture and retested for friction with the BPT to determine the terminal polish value. The British wheel was used extensively in the past for evaluating Virginia aggregates. The proper preparation of test coupons is tedious and time-consuming. Because the method is limited to a single source per specimen and it is unlikely a new series of tests would contribute new information regarding aggregate sources, it was not used in this study.

### *NCAT Polishing Machine*

The NCAT polishing machine consists of a steel frame to which a vertical shaft is attached that holds an assembly of three small wheels rotating on a circular track 11.2 in (285 mm) in diameter. The track is of the same diameter as the circular texture meter (CTM) and dynamic friction tester (DFT) used to determine the microtexture and macrotexture of the asphalt concrete specimens. The applied load on the wheels is variable and can be adjusted by adding/removing circular iron plates on the device's turning table. Water can be supplied from a spray system onto the specimen during testing. The spray system is controlled by a cutoff valve connected to an electronic counter that cuts off the water supply when the desired number of revolutions has been reached. The drawback of this system lies in the fact that it can polish only a small circular area and texture and friction results may be influenced by the positioning of the respective devices onto the polished ring.

## **Materials**

Asphalt mixture samples containing carbonate aggregate in various proportions were collected from VDOT's Bristol and Salem districts in consultation with the study's technical review panel to ensure their interests are being met. The surface mixtures were selected such that in addition to the carbonate aggregate and RAP, which may contain carbonate or non-carbonated aggregate depending on its source, they would contain some percentage of non-polishing aggregate (e.g., granite or quartzite). The mixtures were being commercially produced. The two mixtures sampled from the Bristol District were used in VDOT resurfacing projects, and the mixture sampled from the Salem District was a non-VDOT project. Mixtures tested for polishing in the laboratory were an SM-9.5 (9.5 mm) mixture and a dense-graded SM-12.5 (12.5 mm) mixture. Additional details regarding the mixtures sampled and tested in this study including the design asphalt content and binder grade, the amount of RAP used, and material sources are shown in Tables 1 and 2. Tables 3 and 4 contain data on aggregate gradation and mixture volumetrics.

**Table 1. Surface Mixture Job-Mix Formulas: Bristol District**

<b>Mix Type/ ID No.</b>	<b>Materials</b>	<b>Mix Phase (%)</b>	<b>Source</b>	<b>Location (Year Placed)</b>
SM-9.5AL/ 51010	Limestone No. 8	30	Glade Stone, Glade Springs, VA	Johnston Memorial Hospital Parking Lot, Washington County (2011)
	RAP	10	W-L Construction & Paving, VA	
	Sand	-	-	
	Screening No. 10	60	Glade Stone, Glade Springs, VA	
	Asphalt PG 64-22	5.8	Bristol Asphalt Products, Bristol, VA	
	LOF-6500 Additive	0.6	ARR-MAZZ Products, Winter Haven, FL	
SM- 12.5AL/ 201201	Limestone No. 68	28	USA Aggregates, Abingdon, VA	Rts.11 and 611, Washington County (2011)
	Limestone No. 8	10	USA Aggregates, Abingdon, VA	
	Limestone No. 9	10	USA Aggregates, Abingdon, VA	
	RAP	20	W-L Construction & Paving, Abingdon, VA	
	Black Sand	12	USA Aggregates, Abingdon, VA	
	Screenings	20	USA Aggregates, Abingdon, VA	
	Asphalt PG 64-22	5.7	Bristol Asphalt Products, Bristol, VA	
	LOF-6500 Additive	0.6	ARR-MAZZ Products, Winter Haven, FL	
SM-12.5A/ 1029	Granite No. 68	5	Maymead Materials, Mountain City, TN	Rt. 16, Smyth County (2011)
	Granite No. 8	35	Maymead Materials, Mountain City, TN	
	RAP	22	W-L Construction & Paving, Glade Springs, VA	
	Screenings No. 10 Dry	27	Glade Stone, Glade Springs, VA	
	Limestone Screenings No. 10 Washed	11	Glade Stone, Glade Springs, VA	
	Asphalt PG 64-22	5.7	Bristol Asphalt Products, Bristol, VA	
	LOF-6500 Additive	0.6	ARR-MAZZ Products, Winter Haven, FL	

RAP = recycled asphalt pavement.

**Table 2. Surface Mixture Job-Mix Formulas: Salem District**

Mix Type/ ID No.	Materials	Mix Phase (%)	Source	Location (Year Placed)
SM-9.5DHR/ 2025-2010-05/ 2018-2010-02	Quartzite No. 8	42	Salem Stone, Sylvatus, VA	Rt. 460E, Giles County (2010-2011) Rt. 177S (2011)
	RAP	25	Adams Construction Company, ROA, VA	
	Concrete Sand	20	Whyte Sand, Whyteville, VA	
	Screening (Quartzite) No. 10	13	Glade Stone, Glade Springs, VA	
	Asphalt PG 64-22	5.7	Associated Asphalt Inc., Roanoke, VA	
	Adhere HP + Additive	0.5	ARR-MAZZ Products, Winter Haven, FL	
SM-9.5A/ 2001-99-17	Quartzite No. 8	50	Salem Stone, Sylvatus, VA	Smart Road, Section D (1999)
	Quartzite No. 10	30	Salem Stone, Sylvatus, VA	
	Processed RAP	10	Adams Construction Company, Blacksburg, VA	
	Concrete Sand	10	Whyte Sand, Whyteville, VA	
	Asphalt PG 64-22	5.6	Associated Asphalt Inc., Roanoke, VA	
	Adhere HP + Additive	0.75	ARR-MAZZ Products, Winter Haven, FL	
SM-12.5D/ 1029	Quartzite No. 78	15	Salem Stone, Sylvatus, VA	Smart Road, Section A (1999)
	Quartzite No. 8	30	Salem Stone, Sylvatus, VA	
	Quartzite No. 9	10	Salem Stone, Sylvatus, VA	
	No. 10 Limestone	15	Sisson & Ryan Quarry, Shawsville, VA	
	Sand	10	Castle Sands Company, New Castle, VA	
	Processed RAP	20	Glade Stone, Glade Springs, VA	
	Asphalt PG 64-22	5.6	Bristol Asphalt Products, Bristol, VA	
	Adhere HP + Additive	0.5	ARR-MAZZ Products, Winter Haven, FL	
SM-12.5DL/ 1029	Limestone No. 68	45	ACCO Stone, Blacksburg, VA	Montgomery Executive Airport, Blacksburg ( 2011)
	Quartzite No. 10	45	Salem Stone Company, Sylvatus, VA	
	Sand	10	Whyte Sand Company, Whyteville, VA	
	RAP	0	-	
	Asphalt PG 70-22	5.5	Associated Asphalt Inc., Roanoke, VA	
	Adhere HP + Additive	0.5	Adams Construction Company, Roanoke, VA	

RAP = recycled asphalt pavement,

**Table 3. Surface Mixture Aggregate Gradation and Volumetrics: Bristol District**

Parameter	Mixture Type		
	SM-9.5AL	SM-12.5AL	SM-12.5A
3/4 in (% Pass)	-	100	100
1/2 in	100	97.2	96
3/8 in	95	90	89
No. 4	62	-	-
No. 8	41	37	36
No. 200	6	6.5	6
VTM	4	4	4

VTM = voids in total materials

**Table 4. Surface Mixture Aggregate Gradation and Volumetrics: Salem District**

Parameter	Mixture Type			
	SM-9.5A	SM-9.5DHR	SM-12.5D	SM-12.5DL
3/4 in	-	-	100	100
1/2 in	100	100	96	76.8
3/8 in	90	93	87	54.4
No. 4	56	59	-	13.8
No. 8	34	42	36	2.5
No. 200	6	5.8	5	1.5
VTM	4	3.5	4	3.4
VFA	-	77.9	-	-
VMA	-	15.9	16.6	16.1
P <sub>be</sub>	-	5.56	-	5.48

VTM = voids in total materials VFA = voids in fine aggregate; VMA = voids in mineral aggregates; P<sub>be</sub> = effective asphalt content.

### Specimen Preparation

Two types of asphalt concrete specimens were tested in this study. One type was prepared using the linear kneading compactor at the FHWA's Turner-Fairbank Highway Research Center. This equipment produces slabs that are used for testing asphalt mixtures for various properties and was selected because it was capable of fabricating specimens of the desired size. A weighed mixture is placed in a steel mold in the compactor and a series of vertically aligned steel plates are parallel-positioned on top of it. A steel roller then transmits a rolling action force through the steel plates, one plate at a time, as the mold, mixture, and steel plates move back and forth on a sliding table under the roller. The mixture is kneaded and compressed into a flat slab of predetermined thickness and density. During this kneading action, only a fraction of the mixture is compacted at any given time, thus allowing the mixture to be compacted without excessively fracturing the aggregate.

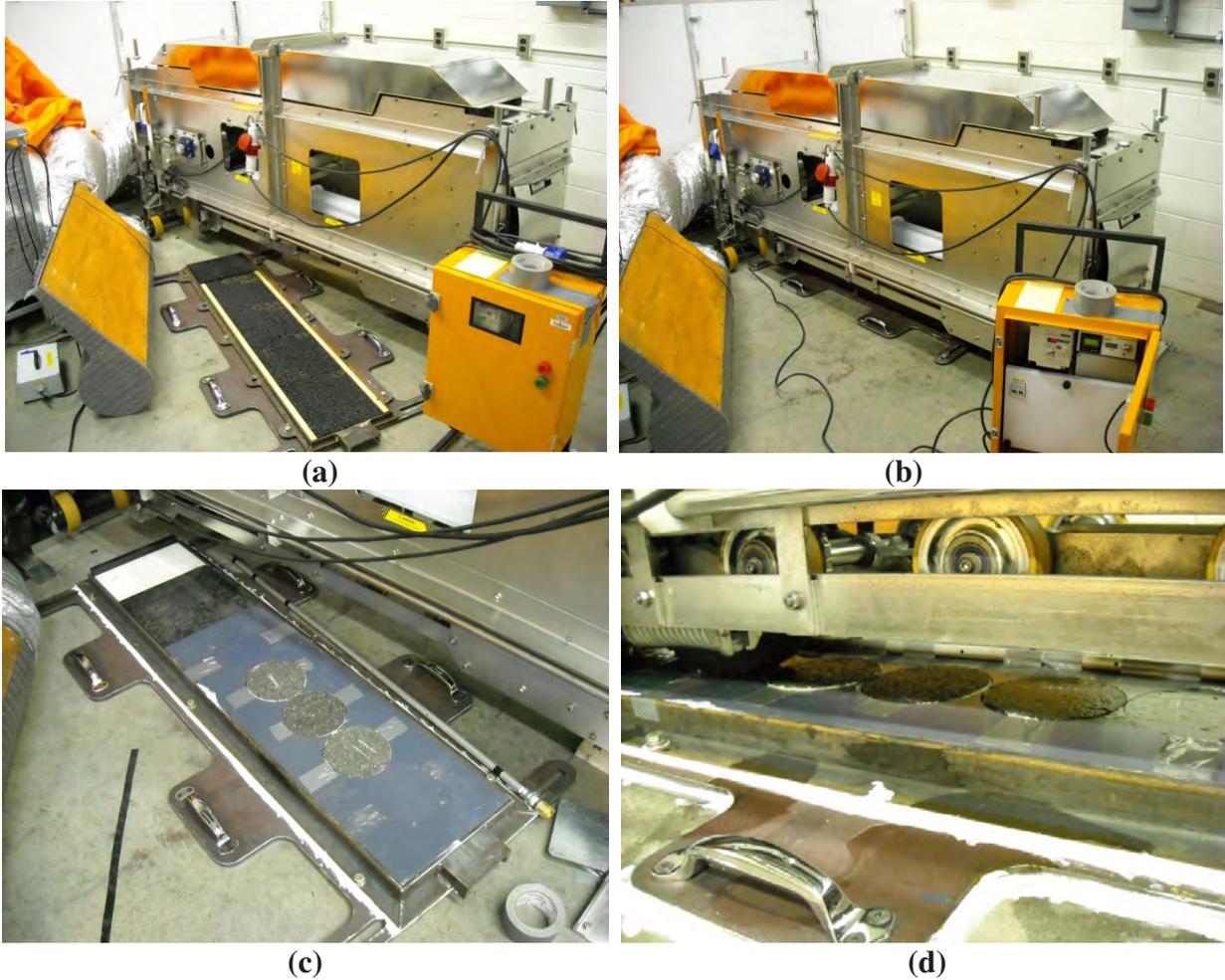
The density of the mixture at the required air-void level and the dimensions of the slab are used to calculate the mass of mixture needed by the trial-and-error method. To achieve the desired density in the slab, the mixture is compacted for about 15 to 20 min after being placed in the mold. The dimensions of the rectangular slabs tested for polishing were 10.6 in by 12 in by 1.2 in tall (267 mm by 305 mm by 32 mm) and were compacted to around a 7% air-void content using the linear kneading compactor. Four slabs with same dimensions were prepared out of each loose mixture sampled from the plant.

The second type of specimens tested for polishing were 6-in-diameter plugs cored from actual pavement sections in the Bristol District. These mixtures contained various percentages of limestone aggregate and RAP. Information on these mixtures was provided by Wang et al. (2010). All mixtures were dense-graded surface mixtures, SM-12.5 A and D, and were placed in 2006. The acquired cores were cut to 1.5 in thick to fit into the testing frame of the trafficking machine (Figure 1).

A proposed new method in this study involved the use of an accelerated trafficking machine, or mobile load simulator. A third-scale model mobile load simulator (MMLS3) was employed as a means for accelerated polishing of the laboratory-compacted specimens. In this system, the load was scaled down to approximately 600 lb but the tire pressure was kept at the same level as real-traffic vehicles. Load frequency, tire pressure, testing temperature, and speed can be adjusted in this equipment. The MMLS3 consists of four rotating axles (bogies) equipped with a pneumatic tire 300 mm (11.8 in) in diameter. The load level on each tire can vary from 2.1 kN (471 lb) to 2.7 kN (606 lb) through adjustment of the suspension system. The tire pressure can be brought up to 800 kPa (115 psi). This equipment is capable of applying up to 7,200 loads per hour. Figure 1 shows the MMLS3, the slab testing frame and base steel plate with the specimens installed, and the machine control box.

The dimensions of the steel testing frame are 60 in by 12 in by 1 to 5 in in height, and it can accommodate various materials (e.g., asphalt, concrete, etc.) slabs in different dimensions with the use of a wide range of spacers for alignment. For the polishing of the asphalt slabs and pavement cores, the load on the machine tires was adjusted down to 400 lb (from a maximum of 600 lb) to prevent rutting of the specimens. To increase the polishing area/width of the slabs and to avoid further rutting of the slabs the wandering mode of the machine was selected during trafficking. In this mode, the machine was set to wander 1.5 in, thus increasing the tested width to 5 in from 3 in, which is the width of the inflated tire at 100 psi. Hence, each half of the asphalt concrete slabs (i.e., about 5.5 in) was tested in cycles of 200K wheel passes, followed by texture and friction measurements using the standardized procedures and devices described in the following section. As can be seen in Figure 1 four slabs were tested at a time for each of the three selected mixtures containing high amounts of limestone.

The cored specimens were tested for polishing in cycles of 100K wheel passes as they had already been trafficked for more than a year and some of the asphalt had been removed from the aggregate. When these samples were tested, the machine wandering mode was adjusted to 2 in so that the entire area of the specimens was covered. To accelerate the polishing progression of the surface of the specimens, a thin layer of a high-strength epoxy mixed with standard graded sand (ASTM C778) (ASTM International, 2006) was applied to the surface of the tires. This process was repeated after each cycle of 200K wheel passes. In addition, a water spray system was used during polishing of the specimens that was kept running continuously for each cycle. The system consists of a 4-ft-long aluminum pipe provided with 1/8-in (3-mm) holes equally spaced through which water is supplied over the surface of the specimens. This way, abraded rubber, epoxy, and sand particles from the tires and removed asphalt from the aggregate are washed off so that wet traffic conditions are being simulated.



**Figure 1. Polishing of Asphalt Concrete Slabs and Pavement Cores Using the MMLS system: (a) slabs before testing, (b) frame being fastened under the MMLS3; (c) pavement cores before being polished; (d) pavement cores during polishing (water spray system shown in the back).**

## **Laboratory Friction and Texture Measurements**

Three devices were used in this study to measure the surface texture and friction of the polished specimens in the laboratory. The same devices were also used for field measurements of asphalt pavement sections with the same and different mixtures for comparison purposes. A fourth device, the locked-wheel skid tester (LWT) was employed to measure the friction properties of asphalt pavement sections at high speeds.

### **Friction Measurements**

#### *British Pendulum Tester (ASTM E303)*

The BPT provides a British pendulum number (BPN) based on the pendulum swing height of a calibrated system. The method has been used with satisfactory results by most departments of transportation in the last four decades (Crowley and Parker, 2001; Mahone, 1975;

Mahone and Sherwood, 1995). For testing, the pendulum is raised to a locked position and then released, thus producing a low-speed sliding contact between a standard rubber slider and the wet pavement / specimen surface. The length of the contact path is between 124 and 127 mm. The elevation to which the drag pointer swings after contact provides an indicator of the frictional properties. Hence, the greater the friction between the slider and the test surface, the more the swing is retarded and the larger the BPN reading (higher number down on the pendulum scale). Conceptually, the measurement is a function of the combined effects of the microtexture and macrotexture of the surface measured.

Typically, data from four swings are collected and recorded with the surface being re-wetted before each swing. In this study, BPNs were collected by swinging of the pendulum in the middle of the specimen, whether slab or cored disc, in the same direction with the MMLS3 trafficking wheels. Several measurements were taken along the length of the slabs, 3 in in each direction, to check the reliability of the readings. No large variations in measurements were observed. Figure 2 illustrates the setup for testing in the laboratory. The same procedure was followed for field measurements. The readings were taken in the right-hand lane (truck lane) in the left wheel path and between wheel paths in the same direction as the traffic.



**Figure 2. British Pendulum Tester Testing Asphalt Concrete Slabs**

#### *Dynamic Friction Tester (ASTM E1911)*

Like the BPT, the DFT is used for microtexture measurements at low speeds, producing DFT numbers or friction coefficients and a graph of the friction coefficient for different rotational speeds, typically 12, 24, 36, and 48 mph (20, 40, 60, and 80 km/h). The device consists of three spring rubber sliders that make contact with the tested surface as the spinning disc that holds them is dropped onto the surface (Figure 3). During testing, water is supplied continuously to the surface. DFT friction measurements in the field were performed consistently with the BPT, meaning that three wheel path and between wheel path readings were acquired in the selected pavement section. However, because of differences in the devices, the directionality of BPT measurements cannot be accommodated with the DFT.



**Figure 3. Dynamic Friction Testing of Asphalt Concrete Slabs in the Laboratory. Left, the slab arrangement for the SM-9.5AL mixture depicting the slabs polished for 100K wheel passes with (upper left / bottom right) and without the epoxy/sand applied to the tires.**

In the laboratory, the four slabs were tested after each cycle of 200K wheel passes. They were adjacently positioned in a 2 by 2 parallel configuration, providing a testing area of 24 in by 21 in; then, the device was placed on the surface as illustrated in Figure 3. Three measurements were recorded with the device being moved slightly (about 2 in) to the left and right from a central position on the slabs arrangement to check for consistency and the reliability of the results.

#### *Locked-Wheel Skid Tester (ASTM E 274)*

The LWT is the most commonly used method in the United States for friction or skid resistance measurements. The device records the steady state friction force of a locked wheel on a wetted pavement surface as the wheel slides at constant speed, typically 40 mph (64 km/h). However, because of safety issues, tests on some roads are conducted at 50 mph (81 km/h) or 30 mph (48 km/h). During testing, the wheel remains locked for approximately 1 sec (e.g., total slip), and the data are measured and averaged. The skid resistance of the paved surface is reported as the skid number (SN), which is the force required to slide the locked test tire at the stated speed divided by the effective wheel load and multiplied by 100 (ASTM E274). The ribbed tire (ASTM E501) is the main tire used with the LWT; however, there is an increasing use of the smooth tire (ASTM E524), as it has been confirmed that the ribbed tire does not perceive macrotexture and, thus, can fail to detect very slippery conditions (Hall et al., 2009). These researchers strongly recommended that agencies consider the use of the smooth tire, which has long been VDOT's practice, when testing for friction. In this study, all measurements on the selected asphalt pavement sections were conducted using the smooth tire.

### **Texture Measurements**

#### *Circular Texture Meter (ASTM E2157)*

The CTM is a non-contact laser device that measures the surface profile along a circular path 11.25 in (286 mm) in diameter at intervals of 0.034 in (0.868 mm) (AASHTO, 2007). The

device was designed to measure the same circular track measured by the DFT. The CTM, which is used for measuring and analyzing pavement macrotexture profiles, rotates at 20 ft/min (6 m/min) and generates profile traces of the pavement surface, which are transmitted and stored on a portable computer. Two different macrotexture indices can be computed from these profiles: mean profile depth (MPD) and root mean square. The MPD, which is a two-dimensional estimate of the three-dimensional mean texture depth (Flintsch et al., 2003), represents the average of the highest profile peaks occurring within eight individual segments comprising the circle of measurement. The root mean square is a statistical value, which offers a measure of how much the actual data (measured profile) deviate from a best fit (modeled profile) of the data.

Good correlations with the sand patch test were obtained from various testing studies in recent years (Mokarem, 2006; Prowell and Hanson, 2005). In this study, the CTM was used to test asphalt concrete slabs in the laboratory, before and after polishing, and pavement sections surfaced with the same mixtures. The CTM was placed in the same three spots as the DFT unit for all measurements. Figure 4 shows the similar slab configuration being tested by the CTM.



Figure 4. Macrotexture Measurement of Asphalt Concrete Slabs Using the Circular Texture Meter

### Field Measurements

All field measurements were taken at about the middle of the selected pavement section in the right-hand lane (truck lane). At each location, three measurements were taken with the CTM and DFT, 2 ft apart in the left wheel path and between wheel paths. Four measurements were taken with the BPT at only one location, the middle spot of the CTM-DFT measurements (i.e., 2 ft away from the first location where these numbers were obtained), in the wheel path and between wheel paths (center of the lane). All measurements were taken on flat and clean surfaces, free of any loose small aggregates, sand, and debris. LWT measurements were taken at 40 mph (60 km/h) at all locations. A similar data acquisition procedure was employed in the laboratory after each polishing cycle. Most field tests were conducted at the same pavement temperatures. The pavement temperatures were higher at only two locations: the Montgomery Executive Airport (103 °F) and Rt. 16, Smyth County (86 °F).

## RESULTS AND DISCUSSION

### MMLS3 Polishing Results

Images showing the surfaces of the laboratory-compacted specimens and pavement cores after different numbers of polishing cycles are presented in Figures 5 and 6, respectively. Although difficult to discern in the figures, direct visual examination suggested that more polishing was induced on the SM-9.5AL and SM-12.5DL mixtures that contained the highest amount of limestone aggregates (over 50%) as both coarse and fine aggregate. The SM-12.5A mixture that had about 40% limestone fine aggregate and 40% granite coarse aggregate, in addition to RAP, underwent comparatively less polish.

For the pavement cores, measurements were made every 50K cycles as the asphalt covering the aggregates was much more oxidized and was being removed at a higher rate. From Figure 6 it appears that the most polishing occurred on the SM-12.5D mixture that contained the lowest amount of limestone (Core 11). A possible reason could be the fact that the top size aggregate appeared to be very fine and the surface of the core exhibited fairly low macrotexture. At the time of the coring, around 2007, it was noted that the cores from the Tazewell County section showed minimal macrotexture when compared to cores from the Russell County and Buchanan County sections.

Figure 7 shows images of asphalt pavement sections in the Bristol and Salem districts that were tested for friction and texture. Some of these sections contained the same mixtures as the slabs that were polished in the laboratory, and they were tested for friction to compare the obtained results with the laboratory results. Other mixtures that had lower percentages of carbonate aggregate (e.g., Smart Road, Section A, with limestone fines) or no carbonates were also tested for friction/texture for comparison purposes. In contrast with the laboratory results, the SM-12.5A pavement section showed the most aggregate exposure, after 1 year of vehicle trafficking; the SM-9.5A and SM-12.5DL mixtures retained the asphalt film on the aggregate particles. This may reflect differences in the traffic nature (speed, braking) and volume between the sites. The 12.5DL mixture, a 45% limestone, 45% quartzite blend, showed very good performance for both polishing and friction.

### Friction and Texture Measurements

Mean values of field and laboratory measurements of the texture and friction characteristics of these mixtures are presented in Tables 5 through 7. Figures 8 through 11 illustrate the variation in the DFT coefficient of friction ( $\mu$ ), the CTM MPD, and the BPN for the three asphalt mixtures tested in the laboratory. Mean field values are also provided for these parameters for comparison purposes. In addition, SNs from the LWT are presented in Table 5. All of these measurements were taken to compare the friction results of sections with and without carbonate aggregate. Several measurements on pavements that were resurfaced in 2006 were acquired, and some of the measurements were made on newly paved sections (e.g., Rt. 11).



**9.5AL ~ 0 cycles**



**9.5AL ~ 600K cycles**



**9.5AL ~ 1Mil cycles**



**12.5DL~ 0K**



**12.5DL ~600K**



**12.5DL~ 1Mil**



**12.5A~ 0K**

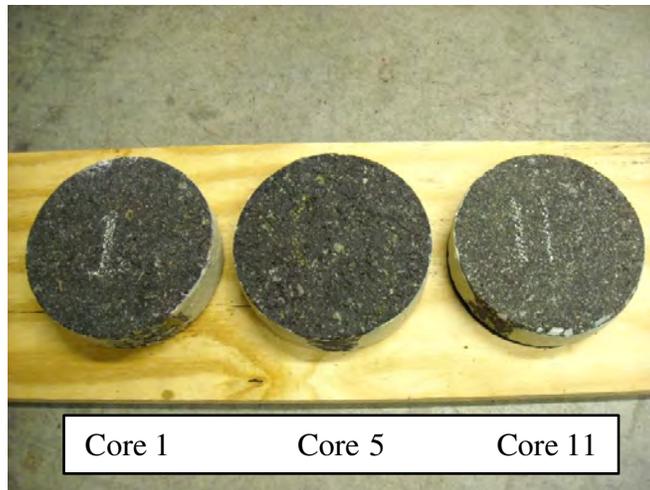


**12.5A ~ 600K**

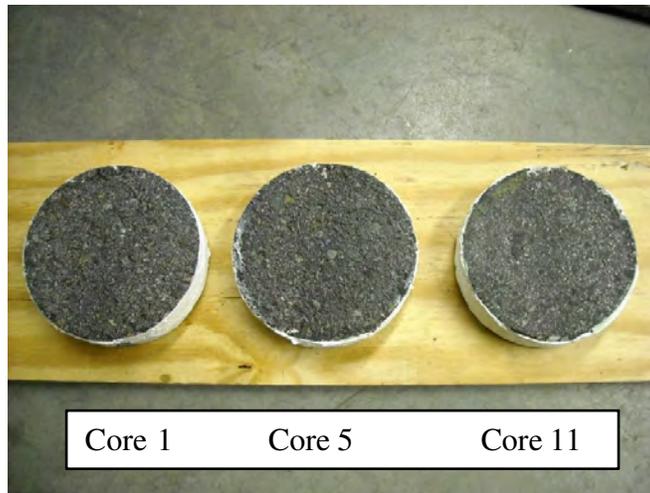


**12.5A~ 1Mil**

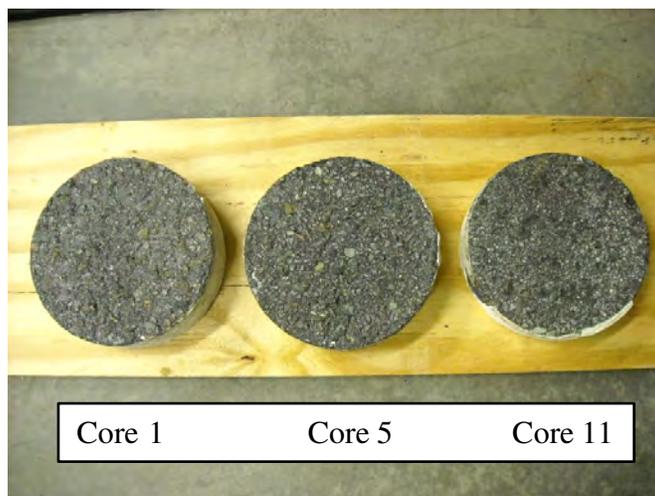
**Figure 5. Laboratory-Polished Slabs Under the MMLS3 (trafficking left to right)**



0 cycles



100K cycles



300K cycles

Figure 6. Laboratory-Polished Pavement Cores Under the MMLS3: Bristol District



**Figure 7. Pavement Sections Selected for Friction/Texture Testing: Salem District. Images taken in 2012, placement year in parentheses.**

**Table 5. Field Friction Texture Measurements**

Location/Mix/(Year Placed)		Test Spot/ Year Tested		Device/Parameter			
				CTM MPD (mm- Mean)	DFT Friction Coefficient ( $\mu$ )*100 (Mean)	BPN (Mean)	SN (Mean)
					20 km/h		
Bristol District Carbonate aggregate (Limestone) (placed 2011)	SM-9.5A Rt. 11S, JMH Washington County	WP/2012	0.58	32	64	30.6	
		BWP/2012	0.69	37	68	N/A	
	SM-12.5A Rt. 16, Smyth County	WP/2012	0.71	36	75	53.7	
		BWP/2012	0.72	32	76	N/A	
	SM-12.5AL Rt. 611 Washington County	WP/2012	0.52	24	69	55.9	
		BWP/2012	0.60	23	72	N/A	
Bristol District Carbonate aggregate Limestone 100% (placed 2011)	SM-12.5AL Rt. 11, SB Washington County	WP	2012	-	-	-	44.7
	SM-12.5AL Rt. 11, NB Washington County	WP	2012	-	-	-	42.0
Bristol District Experimental Carbonate aggregate fines blended with NP coarse	SM-12.5A 44% Carbonate U.S. 460 EBL Buchanan County	WP	2006	-	-	See Table 7	33.9
			2012			-	24.2
	SM-12.5D 35% Carbonate U.S. 460 WBL Tazewell County	WP	2006	-	-	See Table 7	30.4
			2012			-	29.1
	SM-12.5D 50% Carbonate U.S. 58A WBL, Russell County	WP	2006	-	-	See Table 7	37.9
			2012			-	34.6
Salem District Non-carbonate aggregate (Quartzite)	SM-9.5D Rt. 460E Giles County (2000)	WP/2012	0.93	34	65	N/A	
		BWP/2012	0.94	38	66	N/A	
	SM-9.5D HR Rt. 460E TL MP26.41-27.88 Giles County (2011)	WP/2012	0.49	35	70	30.4	
		BWP/2012	0.54	37	73	N/A	
	SM-9.5D HR Rt. 177S Montgomery County (2011)	WP/2012	0.56	38	71	42.2	
		BWP/2012	0.59	40	74	N/A	
Montgomery Executive Airport, Blacksburg	SM-12.5DL Limestone/Quartzite (2011)	WP/2012	-	-	87	72.2	
		BWP/2012	0.28	78	88	N/A	
Smart Road (Quartzite)	SM-9.5A Section D (1999)	WP/2012	0.68	42	82	47.04	
		BWP/2012	0.75	42	87	N/A	
	SM-12.5D Section A (1999)	WP/2012	1.09	40	84	58.9	
		BWP/2012	1.26	44	87	N/A	

CTM MPD = circular texture meter mean profile depth; DFT = dynamic friction tester; BPN = British pendulum number; JMH = James Madison Highway; WP = wheel path; BWP = between wheel paths; NP = non-polishing.

**Table 6. Laboratory Friction Texture Measurements on Asphalt Concrete Slabs**

Mix Type	MMLS3 Wheel Passes (thousands)	CTM MPD (mm-Mean)	DFT Friction Coefficient ( $\mu$ *100 (Mean))	BPN (Mean)
SM-9.5AL Limestone JMH, Bristol (Figures 5,7)	0	0.60	16	66
	200	0.58	18	65
	400	0.55	20	62
	600	0.54	18	59
	800	0.51	14	54
	1000	0.52	13	50
SM-12.5A Granite/Limestone Rt. 16, Bristol (Figures 5,7)	0	0.82	23	76
	200	0.83	26	75
	400	0.94	25	68
	600	0.96	22	64
	800	0.99	21	56
	1000	1.01	19	51
SM-12.5DL Limestone/Quartzite Blacksburg Airport (Figures 5,7)	0	0.63	18	73
	200	0.70	21	71
	400	0.71	22	66
	600	0.73	21	58
	800	0.66	20	53
	1000	0.65	17	48

CTM MPD = circular texture meter mean profile depth; DFT = dynamic friction tester; BPN = British pendulum number; JMH =James Madison Highway.

**Table 7. Laboratory Friction Measurements on Pavement Cores: Bristol District Carbonate Blend Experimental Sites**

MMLS3 Wheel Passes (thousands)	BPN (Mean)		
	SM-12.5D Granite/Limestone (50/50) U.S. 58A WBL Russell County (Core 1 <sup>a</sup> )	SM-12.5A Granite/Limestone (50/50) U.S. 460 EBL Buchanan County (Core 5 <sup>a</sup> )	SM-12.5D Quartzite/Limestone (65/35) U.S. 460 WBL Tazewell County (Core 11 <sup>a</sup> )
0	77	72	73
50	74	69	71
100	69	66	65
150	64	64	62
200	59	57	56
250	60	56	55
300	58	57	53

<sup>a</sup> See Figure 6.

## DFT Results

The DFT values obtained on the laboratory-prepared specimens subjected to MMLS3 polishing are shown graphically in Figure 8. Photographs of the slabs at regular intervals are shown in Figure 5. It is evident from Figure 8 that the coefficient of friction initially shows a slight increase up to 400K (about 250K for the SM-12.5A mixture) wheel passes before a steady decline as the number of polishing cycles increases. However, these subtle changes fall within the expected two standard deviations from the mean (D2S) (95% confidence) range of 12 based on the precision of the method for DFT (30 km/h) reported in ASTM E1911 suggesting the changes do not indicate significant change. The DFT values measured on the laboratory specimens were low, with a maximum value of 26 obtained after 200K cycles on the SM-12.5AL

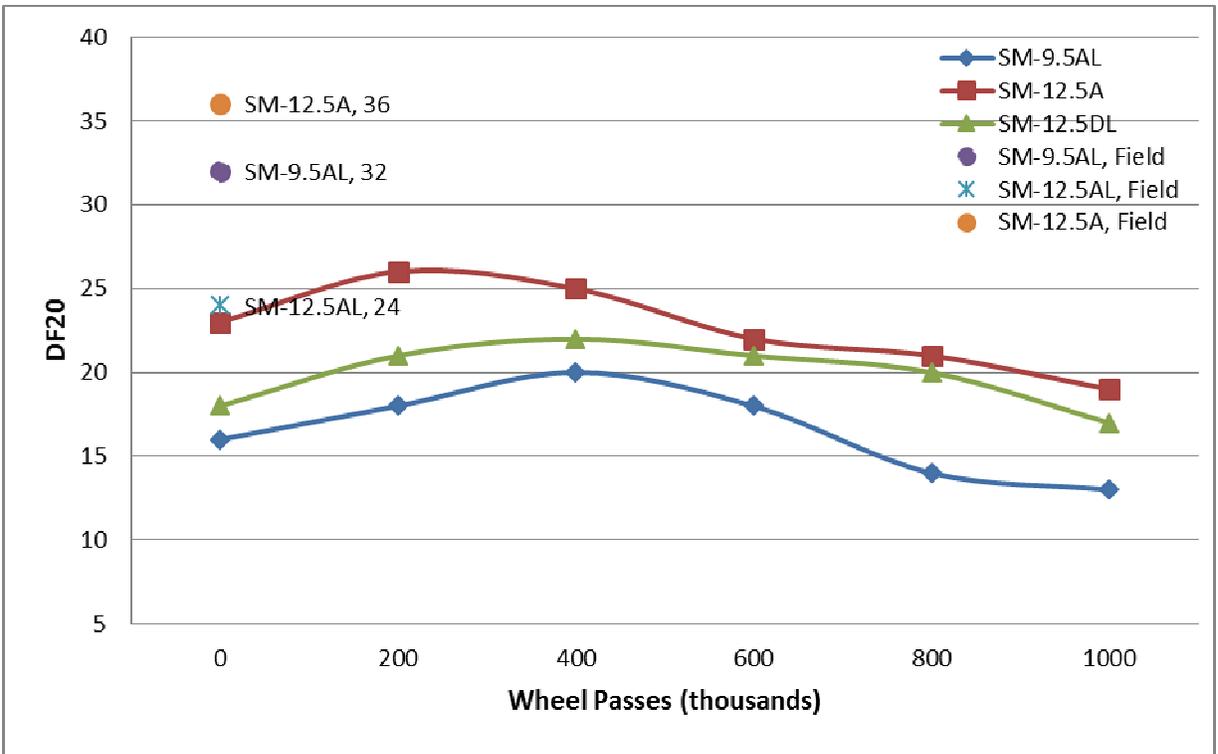


Figure 8. Dynamic Friction Tester (DFT) Coefficient of Friction as a Function of Number of Wheel Passes for Laboratory-Polished Slabs

mixture. Although VDOT does not have a requirement for dynamic friction testing of its asphalt pavement surfaces, friction coefficient values of 25 and above are generally considered acceptable by other states (e.g., Maryland) that use this device for assessing the friction properties of asphalt pavements. Friction coefficient ( $\mu$ ) values as low as 26 and as high as 60 have been reported for Maryland (Groeger et al., 2010).

In field placements (Table 5), the corresponding mixtures exhibited higher DFT values than in the laboratory specimens. For the SM-9.5 mixture, field DFT values of 32 (wheel path) and 37 (between wheel paths) were obtained, and for the SM 12.5A mixture, values of 36 (wheel path) and 32 (between wheel paths) were obtained. These values were roughly comparable to DFT measurements obtained on other field pavements, which ranged from 23 to 42. In contrast, the field measurement for the 12.5DL mixture was anomalously high, at 78.

The increase in DFT values observed after early MMLS3 trafficking cycles of the laboratory specimens is believed to be associated with asphalt removal from the surface of the aggregates before their microtexture is exposed. This phenomenon was also observed in the field in the first 2 years after mixture placement, but it can occur sooner as it is a function of many factors such as traffic volumes, type of asphalt, and weather. The polishing process was stopped after 1 million wheel passes for two reasons: (1) no continued progressive change in friction was expected after these passes (considered as “terminal polish” state); and (2) material densification had been observed in some of the slabs, which led to slight surface distortion and fatigue cracking. This observation raised concerns regarding the accuracy and reliability of the future measurements as the rotating disc of the DFT may have been bouncing on these small

“bumps,” thus affecting the readings. The three “field” values to the left of the graph in Figure 8 represent measurements obtained shortly after placement of the pavement section using the same mixture. Two of the field-placed mixtures, the SM-9.5AL and SM-12.5A mixtures, showed initial values somewhat higher than those of the laboratory-prepared specimens, 32 and 36, respectively. The third field mixture, SM-12.5DL, had an initial value of 78, much higher than that of the corresponding laboratory specimen. Photographs of these pavement surfaces are included in Figure 7.

The low friction values obtained with the DFT in the laboratory can be attributed to the rather thick layer of asphalt covering the aggregates in the specimen and the limited capability of the DFT to remove it during polishing. In addition, a few coarse aggregate particles have been exposed during polishing, making it very difficult for the narrow rubber slides of the DFT to pick up on their microtexture. This was most pronounced for the SM-9.5AL mixture, which also showed the lowest macrotexture. It appears that a relationship exists between the surface texture MPD and the friction coefficients. This is illustrated by a comparison of Figures 8 and 9, wherein the mixtures are similarly ranked for DFT and MPD. A similar relationship can be observed from the field measurements with the exception of the SM-12.5DL mixture (Table 5, Montgomery Executive Airport, Blacksburg), which showed anomalously low MPD values given its DFT friction coefficient, BPN, and SN (i.e., 40) values. However, no similar relationship with the BPT was observed, with BPN values typically much higher than the DFT friction coefficients at 20 km/h.

## **CTM Results**

CTM measurements were performed on laboratory specimens before DFT measurements after each polishing round. The MPD values of the three mixtures containing carbonate aggregate shown in Figure 9 exhibit different trends. The SM-12.5DL mixture mirrors its trend in Figure 8 for DFT results with a progressive increase over early cycles followed by a decrease with later cycles. The MPD of the SM-12.5A mixture progressively increases with wheel passes and the SM-9.5AL mixture shows a slow but steady decline in values. Based on the precision reported in ASTM E2157 the D2S estimate of 0.085 suggests that measurements reflected significant changes in the surface texture of the specimens resulting from the repeated wheel passes was significant. The differences in response during cycling of the SM-12.5DL mixture that showed an increase followed by a decrease and the SM-12.5A mixture that showed a steady increase may reflect the difference in wear resistance of the coarse aggregate in the two mixtures, i.e., limestone and granite, respectively, after being exposed causing increasing texture. Field measurements were also in good agreement with the laboratory results for the two mixtures containing higher percentages of limestone: the SM-9.5AL and SM-12.5A mixtures.

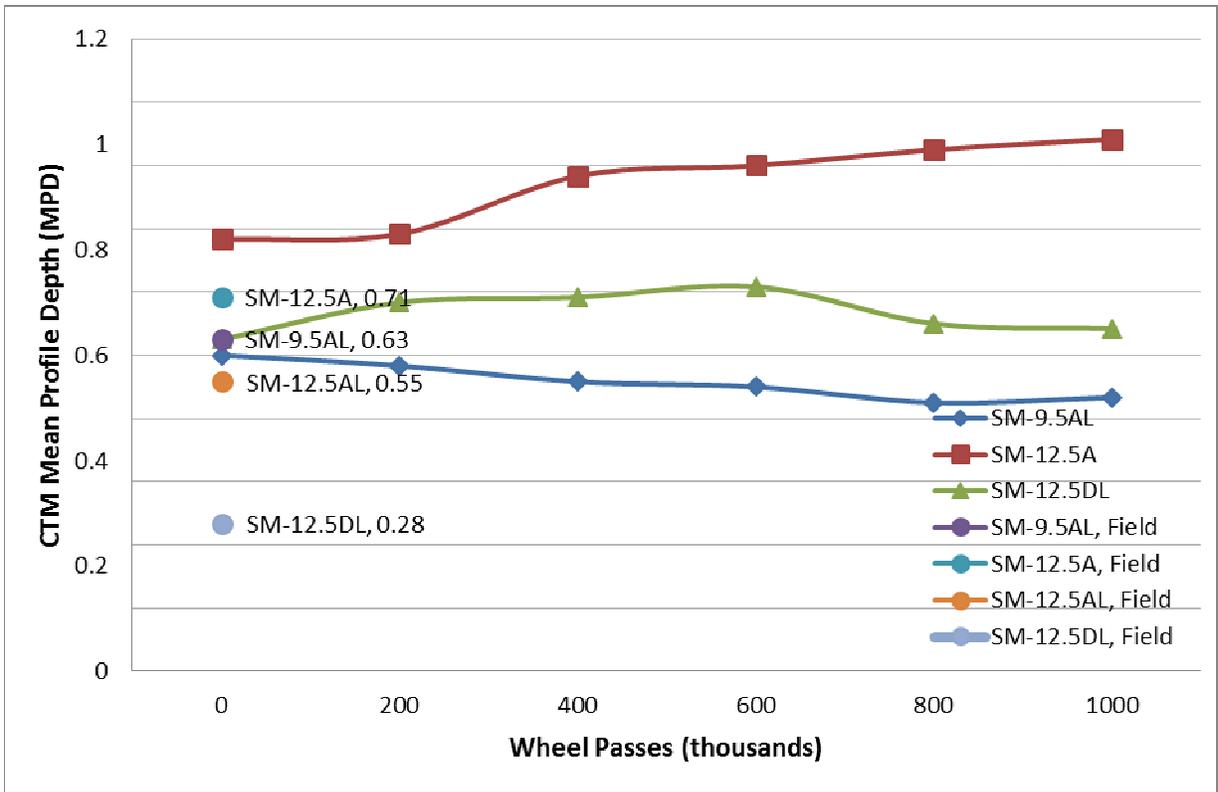


Figure 9. Circular Texture Meter (CTM) Mean Profile Depth (MPD) As a Function of Number of Wheel Passes for Laboratory-Polished Slabs

## BPT Results

As can be seen in Figures 10 and 11, the BPNs show a steady decline for the laboratory-polished slabs and pavement cores. The estimated D2S range for BPN from the reported precision of ASTM E303 was 3.4. The SM-12.5A mixture containing granite coarse aggregate (Table 1) displayed the highest BPNs, and the SM-9.5AL mixture the lowest. Similar results were obtained in the field placements except that the SM-12.5DL mixture displayed the highest BPN (see Figure 7, Blacksburg Airport). For the pavement cores (Figure 11; Table 5, Bristol District experimental mixtures), the 12.5D mixture containing a 50%-50% blend of granite and limestone showed the highest BPNs whereas the 12.5D mixture with a 65%-35% blend of quartzite and limestone showed the lowest BPNs. These measurements were also consistent with the LWT numbers (see Table 5) that showed higher values for the same mixture or the one that had a smaller percentage of limestone in it (i.e., SM-12.5A mixture at 20% limestone). These results are similar to those of Maupin (1979) for asphalt concrete beams containing various aggregate types installed in a pavement section to assess their polishing rate and skid resistance under the accumulated traffic effect. In the current study, the limestone aggregate exhibited the lowest BPNs for the entire monitoring period. For the pavement cores, the authors decided that the terminal polishing condition was reached after 300K wheel passes, as no significant variations in friction numbers were observed after 250K wheel passes.

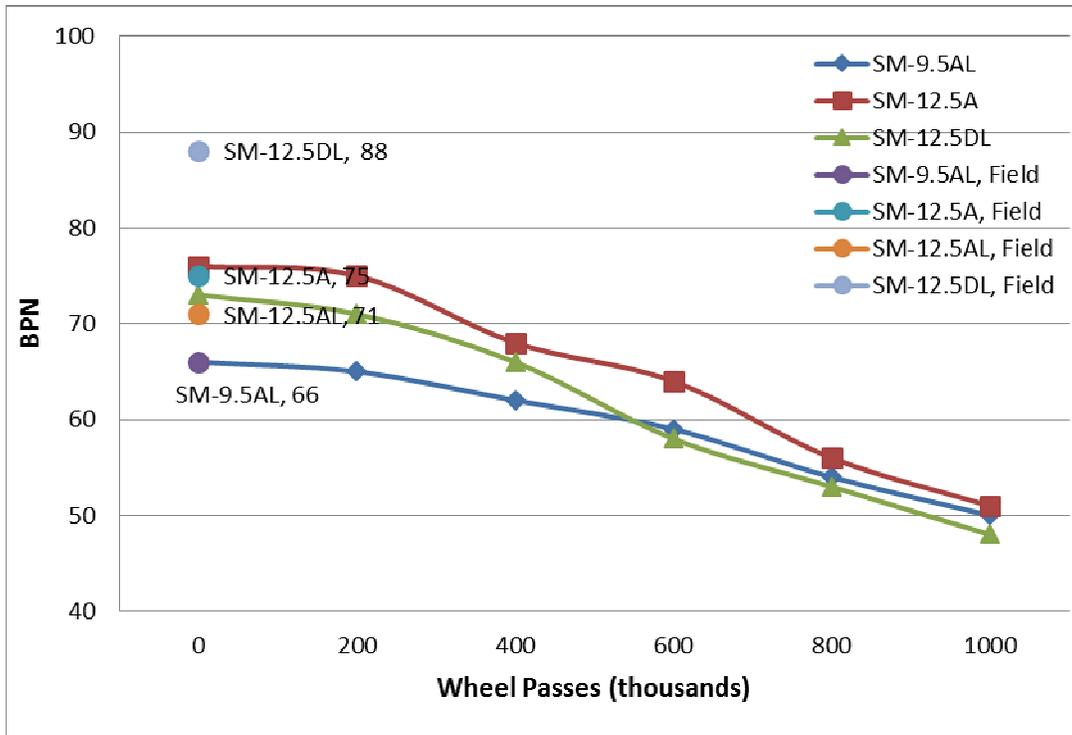


Figure 10. British Pendulum Number (BPN) as a Function of Number of Wheel Passes for Laboratory-Polished Slabs

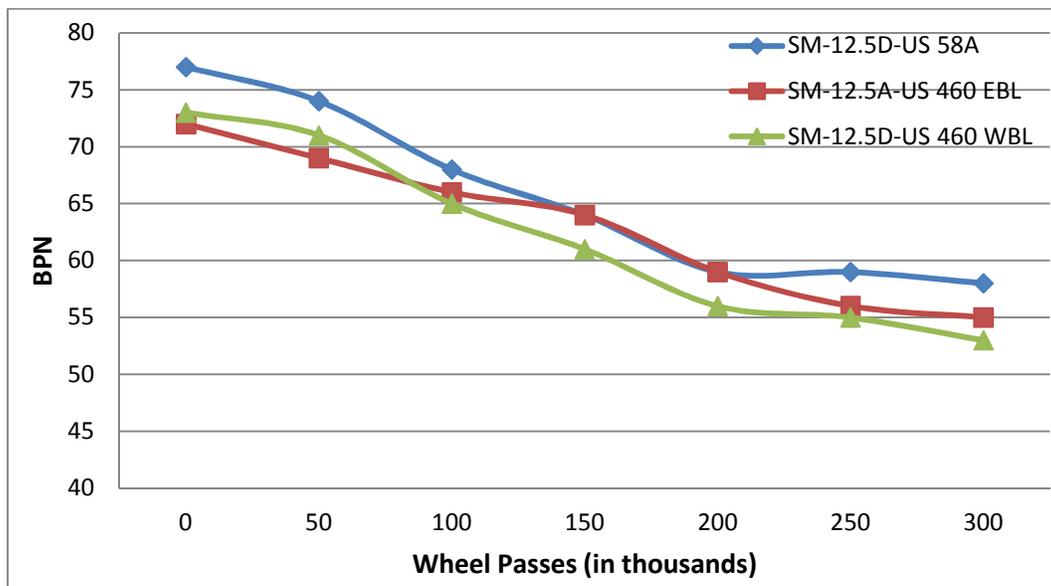


Figure 11. British Pendulum Number (BPN) As a Function of Number of Wheel Passes for Laboratory-Polished Pavement Cores

### Locked-Wheel Skid Tester Results

The LWT testing results from the various pavement sections containing carbonate and non-carbonate aggregates are provided in Table 5. Most of the testing occurred in the summer

for both years (2006 and 2012) with a few tests being conducted in January 2012 (Rt. 16, Smyth County; U.S. 460E, Giles County; Rt. 177, Montgomery County; Johnston Memorial Hospital Parking Lot, SM-9.5AL mixture). The data are provided primarily as a reference point from which to track SNs and frictional properties under trafficking conditions for these pavements. It is anticipated that regular, periodic measurements will be repeated at least every few years to establish a relationship between surface properties and accumulated traffic for these pavement mixtures.

With a few exceptions, initial SNs for the sections were adequate. For example, sections in Smyth County (Rt. 11) and Washington County (Rt. 611) showed relatively high SNs (3.7 and 55.9, respectively) even though the percentage of carbonate aggregate (i.e., limestone) was 100%. Low initial SNs were obtained on several pavement sections including the Bristol District experimental sites in Tazewell County (SN 30.4), and Buchanan County (SN 33.9) surfaced in 2006 and a Salem District section of U.S. 460E in Giles County surfaced in 2011 with an SM-9.5DHR mixture (SN 30.4).

Follow-up skid tests in 2012 on the Bristol District experimental sites showed an insignificant reduction for the Tazewell County pavement (i.e., from 30.4 to 29.2) but a considerable reduction for the Buchanan County site (i.e., from 33.9 to 24.2). The estimated D2S range for SNs based on the precision reported in ASTM E274 was 5.6. The initial measurements on these sites were obtained in 2006. The difference in performance of these two sections is not explained by traffic levels (10K ADT for the Buchanan County site and 20K for the Tazewell County site) but may involve other issues such as the nature of the traffic or peculiarities of the mixtures that result in low pavement surface texture. The carbonate aggregates in these cases were in the fine fractions: No. 10 screenings for the Buchanan and Russell County sites, and a manufactured fine aggregate for the Tazewell County site. The SN for the Russell County site showed a marginal decrease (from 37.9 to 34.6) during the same time frame, with an ADT of 9.6K.

Although an SN of 20 is considered a threshold value by VDOT to flag sites with low friction in the Wet Accident Reduction Program, a study conducted in 2004 by Virginia Tech and VCTIR researchers recommended a higher SN, 25 to 30, in this respect (Kuttesch et al., 2004). If an SN of 25 to 30 is a desired minimum, most of the sites in this study had adequate initial skid resistance. The exceptions were two pavements placed in 2011: the SM-9.5AL mixture at the Johnson Memorial Hospital in Washington County and the SM-9.5D-HR mixture on U.S. 460E in Giles County.

## CONCLUSIONS

- *The MMLS3 can be used to simulate traffic wearing of asphalt concrete specimens of different shapes and sizes in the laboratory including core specimens removed from existing pavements. The machine should be adjusted to the maximum value (i.e., 2 in).*
- *The BPT is effective in characterizing changes in friction on specimens that are subjected to simulated trafficking via the MMLS3.*

- *Test specimens should have a high initial macrotexture and mixtures should have good stability so that the wearing effects are focused on the aggregates.*

## **RECOMMENDATIONS**

1. *VCTIR should work with Virginia Tech and VDOT's western districts to design and conduct an experiment to explore a series of carbonate / non-carbonate aggregate blends for asphalt mixtures. The mixture gradations should be designed to prevent the absence of macrotexture from impacting the ability to measure the "polish" of the coarse aggregate structure of the experimental mixtures.*
2. *VCTIR should work with Virginia Tech to improve the water spray system and to build a system that would circulate the supplied water and abrasive material to the MMLS3 machine during polishing. This way, the number of necessary wheel passes could be reduced.*
3. *VCTIR should purchase tires with different tread patterns and try them on the MMLS3 to evaluate the polishing rate of specimens in more detail.*

## **BENEFITS AND IMPLEMENTATION PROSPECTS**

The ability to increase the use of locally available aggregates while maintaining pavement surfaces with adequate frictional properties offers direct savings in materials and transportation costs and sustainability benefits. This study provided a pathway for continued work toward this goal.

The costs associated with the MMLS3 are very low, as little maintenance is required and training on how to operate the device and collect data is straightforward and brief. Parts and accessories are relatively easy to find, not expensive, durable, and very simple to replace and/or install.

The benefits of the accelerated trafficking system or MMLS3 include portability, meaning it can be operated in the laboratory as well as in the field under various loading conditions, suitability for application of realistic rolling wheel contact stresses on specimens of up to 4 in thick, suitability for testing in wandering mode, thus simulating real traffic conditions, temperature and speed control both indoor and outdoor, wet pavement testing capability, suitability for pre-screening and ranking of full scale APT matrices prior to commencing full scale tests, in order to improve efficiency and cost-effectiveness and provides for the development of acceptance criteria in terms of rutting/fatigue for newly constructed asphalt pavements.

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## REFERENCES

- American Association of State Highway and Transportation Officials. *Guidelines for Skid-Resistant Pavement Design*, Task Force for Pavement Design, Washington, DC, 1976.
- American Association of State Highway and Transportation Officials. *The Guide for Pavement Friction, Guidelines for Skid-Resistant Pavement Design*. Washington, DC, 2007.
- ASTM International. ASTM C778-06: Specification for Standard Sand. In *Annual Book of Standards, Volume 04.01*. West Conshohocken, PA, 2006.
- Anderson, D.A., Meyer, W., and Rosenberger, J.L. Development of a Procedure for Correcting Skid-Resistance Measurements to a Standard End-of-Season Value. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1084. Transportation Research Board of the National Academies, Washington, DC, 1986, pp. 40-48.
- Barksdale, R.D. *The Aggregate Handbook*. National Stone, Sand and Gravel Association, Arlington, VA, 1991.
- Crowley, L., and Parker, F., Jr. Skid Resistance of Asphalt Wearing Courses Made With Limestone Aggregates. Alabama Department of Transportation, Auburn, 2001.
- Flintsch, G.W., Al-Qadi, I.L., Davis, R., and McGhee, K.K. Effect of HMA Properties on Pavement Surface Characteristics. In *Proceedings of the Pavement Evaluation 2002 Conference*, Roanoke, VA, 2002.
- Flintsch, G.W., de Leon, E., McGhee, K.K., and Al-Qadi, I.L. *Pavement Surface Macrotecture Measurement and Application*. Transportation Research Board of the National Academies, Washington, DC, 2003.
- Groeger, J.L., Simpson, A.L., and Pokkuluri, K.S. *Evaluation of Laboratory Tests to Quantify Frictional Properties of Aggregates*. MD-10-SP608B4D. Maryland State Highway Association, Hanover, 2010.

- Habib, A. *2007 Wet Accident Reduction Program (WARP) Report*. Virginia Department of Transportation, Richmond, 2009.
- Hall, J.W., Smith, K.L., Titus-Glover, L., Wambold, J.C., Yager, T.J., and Rado, Z. *Guide for Pavement Friction*. NCHRP Web-Only Document 108. Transportation Research Board of the National Academies, Washington, DC, 2009.
- Henry, J.J. *Evaluation of Pavement Friction Characteristics*. NCHRP Synthesis 291. Transportation Research Board of the National Academies, Washington, DC, 2000.
- Hughes, C.S., and Mahone, D.C. *Blended Aggregate Bituminous Mixes*. VHTRC 75-R39. Virginia Highway Transportation Research Council, Charlottesville, 1975.
- Hughes, C.S., and Mahone, D.C. *Bituminous Mixes Incorporating Blended Aggregates*. VHTRC 79-R49. Virginia Highway Transportation Research Council, Charlottesville, 1979.
- Izeppi, E.L., Flintsch, G.W., and McGhee, K.K. *Field Performance of High Friction Surfaces*. VTRC 10-CR6. Virginia Transportation Research Council, Charlottesville, 2010.
- Jayawickrama, P.W., Prasanna, R., and Senadheera, S.P. Survey of State Practices to Control Skid Resistance on Hot-Mix Asphalt Concrete Pavements. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2026. Transportation Research Board of the National Academies, Washington, DC, 1996, pp. 52-58.
- Kowalski, K.J., McDaniel, R.S., and Olek, J. *Identification of Laboratory Techniques to Optimize Superpave HMA Surface Friction Characteristics*. Final Report IHRB Project TR-450. North Central Superpave Center, West Lafayette, IN, 2010.
- Kuttesch, J.S., Flintsch, G., Al-Qadi, I., Trani, A., and McGhee, K.K. *Quantifying the Relationship Between Skid Resistance and Wet Weather Accidents for Virginia Data*. Master's Thesis. Virginia Polytechnic Institute and State University, Blacksburg, 2004.
- Mahmoud, E., and Masad, E. Experimental Methods for the Evaluation of Aggregate Resistance to Polishing, Abrasion, and Breakage. *Journal of Materials in Civil Engineering*, Vol. 19, No. 11, 2007, pp. 977-985.
- Mahone, D.C. *An Evaluation of the Effects of Tread Depth, Pavement Texture, and Water Film Thickness on Skid Number-Speed Gradients*. VHTRC 75-R40. Virginia Highway Transportation Research Council, Charlottesville, 1975.
- Mahone, D.C., and Sherwood, W.C. *The Effect of Aggregate Type and Mix Design on the Wet Skid Resistance of Bituminous Pavement: Recommendations for Virginia's Wet Accident Reduction Program*. VTRC 96-R10. Virginia Transportation Research Council, Charlottesville, 1995.

- Mahone, D.C., and Sherwood, W.C. *Virginia's Wet Accident Reduction Program: A User's Manual*. VTRC 96-R10. Virginia Transportation Research Council, Charlottesville, 1996.
- Masad, E., Rezaei, A., Chowdhury, A., and Harris, P. Predicting Asphalt Mixture Skid Resistance Based on Aggregate Characteristics. FHWA/TX-09/0-5627-1. Texas Transportation Institute, College Station, 2009.
- Maupin, G.W. *Design of Bituminous Mixes With High Skid Resistance*. VHTRC 80-R11. Virginia Highway Transportation Research Council, Charlottesville, 1979.
- Maupin, G.W. *Use of Limestone Screenings in S-5 Surface Mixes*. VHTRC 82-R54. Virginia Highway Transportation Research Council, Charlottesville, 1982.
- Mokarem, D. *Use of the Digital Surface Roughness Meter in Virginia*. VTRC 07-R4. Virginia Transportation Research Council, Charlottesville, 2006.
- Prowell, B.D., and Hanson, D.I. *Evaluation of Circular Texture Meter for Measuring Surface Texture of Pavements*. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1929. Transportation Research Board of the National Academies, Washington, DC, 2005, pp. 88-96.
- Shaffer, S.J., Christiaen, A.-C., and Rogers, M.J. *TASK 2003E1: Assessment of Friction-Based Pavement Methods and Regulations*. National Transportation Research Center Incorporated, Federal Highway Administration, McLean, VA, 2006.
- Skerritt, W.H. Aggregate Type and Traffic Volume As Controlling Factors in Bituminous Pavement Friction. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1418. Transportation Research Board of the National Academies, Washington, DC, 2007, 1993, pp. 22-29.
- Stroup-Gardiner, M., Studdard, J., and Wagner, C. Evaluation of Hot Mix Asphalt Macro- and Microtexture. *ASTM Journal of Testing and Evaluation*, Vol. 32, No. 1, 2004, pp. 1-10.
- Virginia Department of Transportation. *Road and Bridge Specifications*. Richmond, 2007. <http://www.virginiadot.org/business/const/spec-default.asp>. Accessed June 25, 2014.
- Linbing W., Cristian D., and Lane, D.S. *Methods for Assessing the Polishing Characteristics of Coarse Aggregates for Use in Pavement Surface Layers*. VTRC 10-CR7. Virginia Transportation Research Council, Charlottesville, 2010
- Webb, J.W. *The Wearing Characteristics of Mineral Aggregates in Highway Pavements*. VHTRC 70-R7. Virginia Highway Transportation Research Council, Charlottesville, 1970.