Effect of HMA Properties on Pavement Surface Characteristics

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Abstract. Since the main function of the pavement is to provide a safe and smooth ride to the users or *clients* of the facility, functional characteristics such as safety and comfort must be considered when selecting and designing hot-mix asphalt (HMA) wearing surfaces. This paper discusses an extensive investigation conducted to evaluate the texture and skid resistance properties of seven wearing surfaces used at the Virginia Smart Road. Variation in skid resistance and surface macrotexture measurements due to HMA design characteristics and testing conditions (tire, test vehicle speed, and grade) were analyzed. The mixtures studied include five different SuperPave™ mixes, a stone mastic asphalt (SMA), and an open-graded friction course (OGFC). The evaluation of the surface skid characteristics was based on measurements conducted using a locked-wheel trailer utilizing ASTM-specified ribbed and smooth tires. The macrotexture measurements were conducted using mainly a laser profiler. Statistical results indicated that, for the mixes studied, the roadway slope had insignificant effect on skid number (SN) measurements. Friction measurements, however, are dependent on the tire used, surface texture, age in service, and surface temperature. It was found that HMA design parameters affect pavement surface friction and texture. For the range of mixes studied, the mean profile depth (MPD) can be closely predicted based on the nominal maximum size (NMS) and VMA. Furthermore, the SN measured at 64 km/hr using the ribbed tire ($SN_{(64)R}$) is mostly influenced by the NMS and VTM. The greater the NMS, the lower the ribbed tire skid number. On the other hand, other aggregate parameters and mixture properties have to be considered to accurately predict SN measured at 64 km/hr using the smooth tire ($SN_{(64)S}$).

INTRODUCTION

The current trend towards the use of mechanistic flexible pavement design and analysis procedures has placed a great deal of emphasis on intergraded pavement and HMA systems design. Within this scheme HMA is designed to withstand traffic and environmental conditions expected for a particular roadway section. Since the main function of the pavement is to provide a safe and smooth ride to the drivers, or "clients" of the facility, functional characteristics such as ride quality, safety, and noise must also be optimized. Smoothness specifications have been already implemented by several states (*1*, *2*). However, HMA safety-related texture and skid properties are not yet quantitatively included in most specifications.

The safety of a pavement surface is primarily related to the surface friction, or skid resistance, and surface texture of the pavement. Other distresses such as severe rutting or potholes also have a significant effect. Each year there are between 45,000 and 50,000 accidental fatalities in the U.S., and approximately 15 percent of accidents that result in an injury or a fatality occur during wet weather conditions (*3*). These accidents result from numerous reasons including driver error, vehicle malfunction, and friction deficiencies at the tire-pavement interface. Pavement surface characteristics and vehicle tires are the major contributors to pavement friction. Vehicle speed, braking system, and load distribution also affect the pavement-tire interaction (*4*).

Since it is nearly impossible to control vehicle characteristics affecting skid resistance for every vehicle, it is imperative that pavement surfaces provide adequate friction to minimize the number of accidents that occur as a result of frictional deficiencies. Some of the factors that affect the frictional properties of pavement surfaces include the surface condition (porosity, wear, polishing, rutting, bleeding, and surface contamination) and HMA properties such as aggregate type and gradation (*4*, *5*). Designing and maintaining pavements that provide adequate skid resistance may decrease wet weather accidents.

Although road safety issues have not been systematically included as part of the pavement management process, several authors have discussed the incorporation of pavement-related safety considerations. Li et al. (6) identified the main pavement engineering relationships associated with road safety and safety aspects related to pavement management. The researchers also proposed a systematic approach for coordinating pavement maintenance programs with road safety improvements. This integration has recently proved more important with the advent of the transportation asset management philosophy that is gaining widespread application among transportation agencies.

This paper focuses on the evaluation of the safety and serviceability of seven HMA wearing surfaces used at the Virginia Smart Road under different environmental conditions. In addition, the paper discusses the variation in skid resistance measurements under different testing conditions such as testing tire and speed of the testing vehicle.

PAVEMENT SURFACE CHARACTERISTICS

Pavement surface characteristics are important for both the safety and comfort of drivers. Pavement surfaces should provide adequate friction and maintain a good level of ride quality to ensure satisfaction of the driving public. The combination of good friction, low levels of roughness, and low levels of noise are important in the design of a pavement-wearing surface.

The surface texture of a pavement-wearing surface is one of the primary contributors to tire-pavement friction. Both macrotexture and microtexture affect the friction characteristics of pavement surfaces. Increasing the texture of in-service or new pavement surfaces would increase the skid resistance levels of the pavement. However, this may sometimes increase the level of discomfort for vehicle occupants (*7*). Other negative aspects of increasing pavement friction include increased fuel consumption, tire wear, and noise inside the vehicle. However, the negative aspects of increasing pavement friction are outweighed by the potential decrease in the number of accidents due to inadequate pavement friction (*8*).

Pavement Skid Resistance and Texture Measurement

Pavement texture is the feature of the road surface that ultimately determines most tire road interactions, including wet friction, noise, splash and spray, rolling resistance, and tire wear. Pavement texture has been categorized into three ranges based on the wavelength of its components: microtexture, macrotexture, and megatexture (Table 1). Wavelengths longer than the upper limit of megatexture are defined by the term roughness or evenness.

TABLE 1 Texture Classifications

Texture Classification	Relative Wavelengths
Microtexture	$\lambda < 0.5$ mm
Macrotexture	0.5 mm $< \lambda <$ 50 mm
Megatexture	50 mm $< \lambda <$ 500 mm
Roughness	0.5 m $< \lambda <$ 50 m

Figure 1 illustrates the concept of microtexture and macrotexture. The resistance to skidding on a road surface is largely affected by both microtexture and macrotexture. Good pavement macrotexture allows for the rapid drainage of water from the pavement that, in turn, improves the contact between the tire and the pavement surface. It also provides the hysteresis component of the friction. Microtexture provides direct tire-pavement contact and contributes to the adhesion component of the friction (*9*).

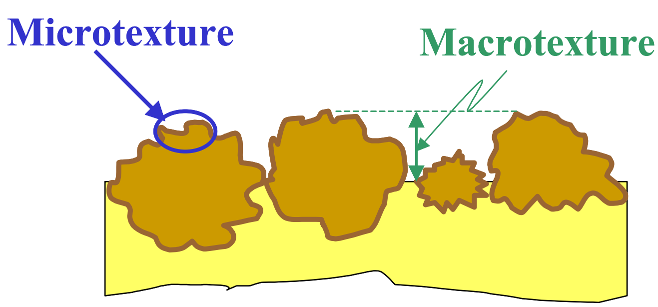

FIGURE 1 Microtexture and Macrotexture Illustration.

A detailed list of different devices currently in use for measuring pavement skid resistance and surface macrotexture is provided by Henry (*9*). A brief description of the main equipment used is presented in the following sections.

Surface Macrotexture

The macrotexture of a pavement surface results from the large aggregate particles in the mixture. Macrotexture measurements can be divided into two main classes: static measurements and dynamic measurements. Common static macrotexture measurement methods include the sand patch method, the outflow meter, and the circular texture meter. The sand patch method (ASTM E965) is a volumetric approach to measuring pavement macrotexture. Because of operator dependency, the test results are not very repeatable. A known volume of sand material is spread properly on a pavement surface to form a circle, thus filling the surface voids up with sand. The diameter of the circle on which the sand material has been spread is measured and used to calculate Mean Texture Depth (MTD).

The outflow meter indirectly estimates the pavement texture based on the time for a fixed volume of water to escape from a measured cylinder with a rubber bottom. The Circular Track Meter, or CTMeter, has a laser displacement sensor mounted on an arm that rotates on a circumference of 142mm radius and measures the texture with a sampling interval of approximately 0.9mm. The profile is measured on the same circumference that the coefficient of friction is measured with a Dynamic Friction Tester (DFT).

Vehicle-mounted laser devices are typically used to measure macrotexture without disrupting traffic flow. A standard method for determining pavement macrotexture from a pavement profile is provided in ASTM Standard E1845 (*11*). The measured profile of the pavement macrotexture is divided for analysis purposes into segments, each having a base-length of 100mm. The slope, if any, of each segment is suppressed by subtracting a linear regression of the segment. The segment is divided in half and the highest peak in each half segment is determined. The difference between the resulting height and the average level of the segment is calculated. The average value of these differences for all segments making up the measured profile is reported as Mean Profile Depth (MPD).

Microtexture Measurements

Microtexture is defined as a surface-roughness quality on the sub-visible or microscopic level. Microtexture, a function of the aggregate particle properties, is not measured directly in the field. Microtexture levels are commonly estimated using low speed friction measurement devices, such as the British Portable Tester or the locked wheel skid trailer when testing is performed at low speeds (*12*). Earlier research has indicated that measurements conducted using the ribbed tire (ASTM E501) are highly sensitive to the microtexture properties of the pavement surface and thus are good estimators of pavement microtexture (*13*).

Skid Resistance

There are different types of equipment that can be used to measure the frictional properties of a pavement surface. The devices can be grouped in four basic classes: locked wheel, side force, fixed slip, and variable slip. These devices operate upon different friction measurement modes and measure different frictional properties of the tire-pavement interaction.

The locked wheel friction measurement device (ASTM E274) is the most commonly used device in the U.S. It depicts the frictional properties of the pavement during the occurrence of an emergency situation in which a vehicle, not equipped with an anti-locking brake system, completely locks its tires (*9*). The test can be performed using a ribbed tire (ASTM E501) or a smooth tire (ASTM E524). Testing performed with the locked wheel trailer in accordance with ASTM E274-97 allows for the computation of the skid number (SN):

$$SN = 100\mu = 100\left(\frac{F}{W}\right) \tag{1}$$

where,
SN = Skid number at the measured speed;
μ = Friction coefficient;
F = Tractive force applied to the tire; and
W = Vertical load applied to the tire.

The side force device uses a wheel that is mounted at an angle to the direction of motion of the test vehicle. The force that is produced on the sideways mounted wheel is used to calculate the friction coefficient of the pavement surface. Fixed slip testers operate with a constant rate of slip, typically around 10 to 20 percent. Variable slip friction measurement devices measure the friction of the pavement surface in a manner similar to the fixed slip devices. However, the slip rate of the test wheel is varied to record a range of friction values (*9*). Some locked wheel testers can also perform tests with the wheel at a variable slip rate, with 0 percent slip indicating that the wheel is freely rolling and 100 percent slip indicating that the wheel is fully locked. Studies have shown that the typical range of maximum friction values occur at 15 to 20 percent slip rates (*10*).

Portable testers are also used to measure the frictional properties of pavement surfaces. These testers use pendulum or slider theory to measure friction in a laboratory or in the field. The British Portable Tester, or BPT, (ASTM E303) is probably the most recognized portable friction measurement device. The Dynamic Friction Tester (ASTM E1911) is also gaining acceptance and provides more information because it allows measuring friction as a function of speed over the range from 0 to 90 km/h.

The International Friction Index

The International Friction Index (IFI) was developed as a common reference scale for quantifying the pavement surface frictional properties (*12*). The IFI uses measurements of skid resistance and texture to evaluate the pavement surface characteristics and is being adopted worldwide for skid resistance comparison. To calculate the IFI it is necessary to have at least one friction measurement and one macrotexture measurement (ASTM E 1960 [*11*]). The importance of good macrotexture is depicted in Figure 2. The IFI is reported in two parameters: the normalized wet friction value at 60 km/hr per hour (F60) and a speed constant (S_p) related to the surface macrotexture. A transformation equation has also been established to allow for calculation of the IFI at speeds other than 60 km/hr.

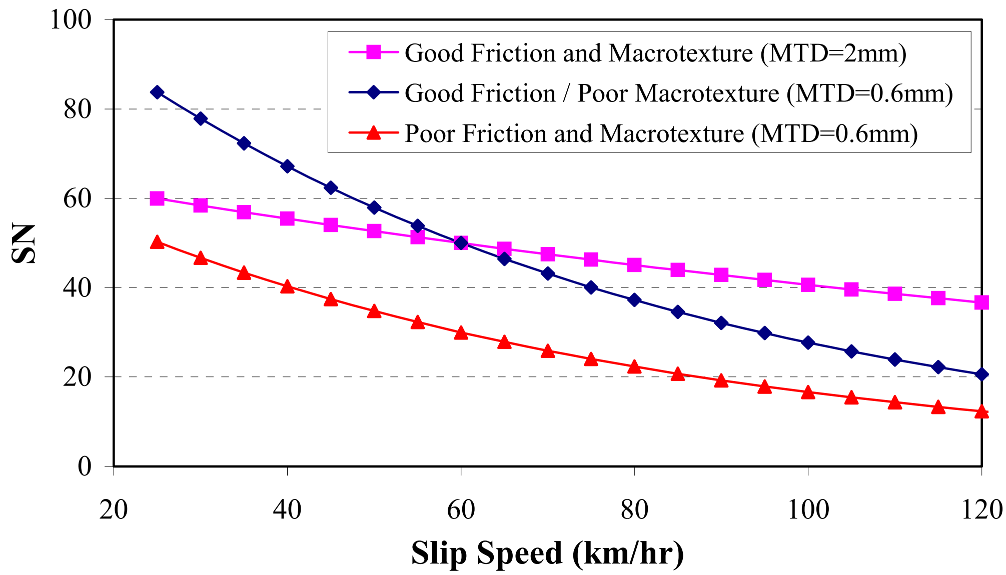

FIGURE 2 Example of Surfaces with Various Degrees of Friction and Macrotexture.

The speed constant, S_p, is calculated using the following equation if an appropriate texture measurement is available.

$$S_p = a + b * TX \qquad (2)$$

where,
TX = Macrotexture parameter (mm); and
a, b = Calibration constants dependent on the method used for determining TX; a=14.2 and b=89.7 if TX is expressed as MPD according to ASTM E 1845

The speed at which the friction parameters are measured is adjusted to the required 60 km/hr using the speed constant and the measured friction values as follows:

$$FR60 = FRS * e^{\frac{S-60}{S_p}} \tag{3}$$

where,
FR60 = Adjusted friction value to 60 km/hr;
FRS = Friction measured by the equipment at the slip speed;
S = Slip speed (km/hr); and
S_p = Speed constant (km/hr).

The adjusted friction value and the texture measurement are then used to calculate the value for F60:

$$F60 = A + B * FR60 + C * TX \tag{4}$$

where,
F60 = Normalized friction value;
A, B, C = Calibration constants dependent upon the measurement equipment used (if the ASTM E274 skid trailer is used: A=0.045, B=0.925, and C=0 for the smooth tire; A=-0.023, B=0.607, and C=0.098 for the ribbed tire);
FR60 = Value calculated using Equation 3; and
TX = Macrotexture measurement (mm).

DATA COLLECTION

The flexible pavement portion of the Virginia Smart Road includes 12 heavily instrumented pavement sections (*14*). These experimental sections include seven different HMA wearing surfaces types (with different nominal maximum sizes, gradations, and asphalt binders) that were chosen to represent the current and proposed wearing surface mixtures used by the Virginia Department of Transportation (VDOT). A detailed evaluation of the surface macrotexture and skid resistance characteristics of the different wearing surfaces was conducted.

HMA Design and Production Properties

The wearing surface mixtures used included five different SuperPave™ mixtures (9.5 mm or 12.5 mm nominal maximum aggregate sizes (NMS)), a 12.5 mm stone mastic asphalt (SMA), and a 12.5 mm open-graded friction course (OGFC). The SM-12.5D, SM-9.5A, SM-9.5D, and SM-9.5E mixtures were designed in accordance with VDOT's 1999 Section 211, Special Provision for SuperPave™ (15). The SMA-12.5, OGFC, and high lab compaction SM-9.5A(H) were experimental mixes. The high lab compaction mix was designed using 75 gyrations for N_{des} instead of the standard 65 gyration used by VDOT for this type of mix. The mixes were produced through a batch plant. Every effort was made to match the design properties. However, two of the mixes (SM-12.5D and OGFC) failed to meet current specifications. The gradation for the SM-12.5D produced was finer (9.5 NMS) than the designed one and the OGFC was constructed with a lower asphalt content than the design target. The seven wearing surface mixes were tested in the laboratory to determine their HMA design properties. Loose samples were taken during placement of the wearing surface from which specimens were prepared in the laboratory in accordance with VDOT mixture design practices. Gradation analysis, ignition, and specific gravity testing were performed to determine volumetric and composition properties of the mixes. The laboratory results are summarized in Table 2.

TABLE 2 Laboratory Measured Properties of the Wearing Surface HMA

Section	Mix Type	Binder Type	Binder Code	Binder Content	Nominal Max.Size	% Pas. #200	VTM @N_{Des}	VMA @N_{Des}
A	SM-12.5D	PG 70-22	0	5.9	9.5	5.9	5.3	17.0
B	SM-9.5D	PG 70-22	0	4.6	9.5	6.7	6.2	16.7
C	SM-9.5E	PG 76-22	1	5.6	9.5	8.4	2.2	14.8
D	SM-9.5A	PG 64-22	-1	5.8	9.5	8.0	0.8	15.0
E	SM-9.5D	PG 70-22	0	5.7	9.5	7.0	3.4	16.1
F	SM-9.5D	PG 70-22	0	5.7	9.5	8.0	3.1	15.9
G	SM-9.5D	PG 70-22	0	5.6	9.5	7.9	2.8	15.3
H	SM-9.5D	PG 70-22	0	5.6	9.5	7.2	3.5	16.2
I	SM-9.5A(h)	PG 64-22	-1	5.2	9.5	7.3	4.2	15.2
J	SM-9.5D	PG 70-22	0	4.9	9.5	6.5	7.1	17.4
K	OGFC	PG 76-22	1	5.5	12.5	1.1	22.4	34.4
L	SMA-12.5D	PG 70-22	0	6.6	12.5	10.5	1.2	15.6

Surface Friction and Texture Measurements

Friction and texture measurements were conducted over a three-year period according to the schedule presented in Table 3. Details of the tests are provided in the following sections.

TABLE 3 Test Schedule

Type of Test	Test Date	Equipment Used
Texture	12/2/99	Laser Profiler
Skid resistance	3/9/00	Locked Wheel Trailer, Smooth Tire
Texture	3/15/00	Laser Profiler
Skid Resistance	3/27/00	Locked Wheel Trailer, Ribbed Tire
Texture	6/20/00	Laser Profiler
Texture	9/14/00	Laser Profiler / Sand Patch Test
Skid resistance	9/19/00	Locked Wheel Trailer, Ribbed Tire
Skid resistance	10/4/00	Locked Wheel Trailer, Smooth Tire
Skid resistance	2/7/01	Locked Wheel Trailer, Smooth and Ribbed Tires
Texture	2/21/01	Laser Profiler
Texture	5/29/01	Laser Profiler
Texture	8/12/01	Laser Profiler / CTM / ROSANv
Skid resistance	8/22-23/01	British Pendulum
Skid resistance	9/25/01	Locked Wheel Trailer, Smooth Tire
Skid resistance	10/03/01	Locked Wheel Trailer, Ribbed Tire
Skid resistance	1/26-27/02	British Pendulum
Texture	3/29/02	Laser Profiler
Texture	4/9/02	Laser Profiler/ CTM / Sand Patch Test
Skid resistance	5/1/02	Locked Wheel Trailer, Smooth and Ribbed Tires

Skid Resistance Measurements

Skid resistance testing of the different Virginia Smart Road flexible pavement sections was performed in both the downhill and uphill directions for both the instrumented and non-instrumented lanes. Both ASTM standard tires, ribbed and smooth, were used in this study throughout the test period. Because of the different types of friction that can occur between a tire and the pavement surface, the type of tire used for testing skid resistance affects the measurement of the pavement surface friction (*16*). For example, past experience has shown that short-term fluctuations resulting from rainfall, temperature, and fluctuating microtexture values were much greater when testing was performed using the ribbed tire than when using the smooth tire (*17*).

Tests were performed at three speeds (32, 64, and 80 km/hr). Three replicates in each lane and direction were performed for each tire. For each replicate, the following data was recorded: average testing speed, average skid numbers, and standard deviation of the speed and the skid number.

Surface Macrotexture Measurements

A laser texture device (International Cybernetics Corporation) was used to measure the texture properties. The first test was conducted in the uphill and downhill directions for both lanes. However, it was determined that the direction of testing did not affect the mean profile depth measured, and the remaining tests were performed in the downhill direction for the non-instrumented lane and the uphill direction for the instrumented lane. The mean profile depth measurements for all sections are shown in Figure 3.

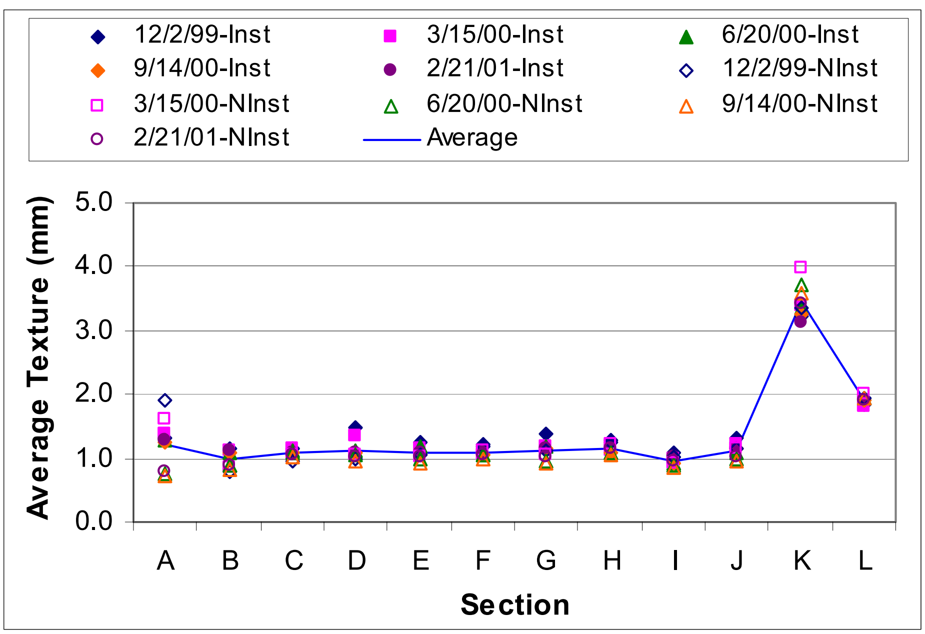

FIGURE 3 Mean Profile Depth Measurements for All Sections.

To obtain ground–truth tests that could be used to compare other macrotexture measurements, a limited number of sand patch tests (ASTM E965) were conducted by an experienced technician on selected sections concurrently, with the fourth laser measurements in September 2000. These tests were conducted either on the left wheel path (LWP) and the center of the lane or between wheel paths (BWP). The comparison of the laser-determined MPD, and sand patch tests (Figure 4) indicated that the relationship may be different from the one used by ASTM E1845.

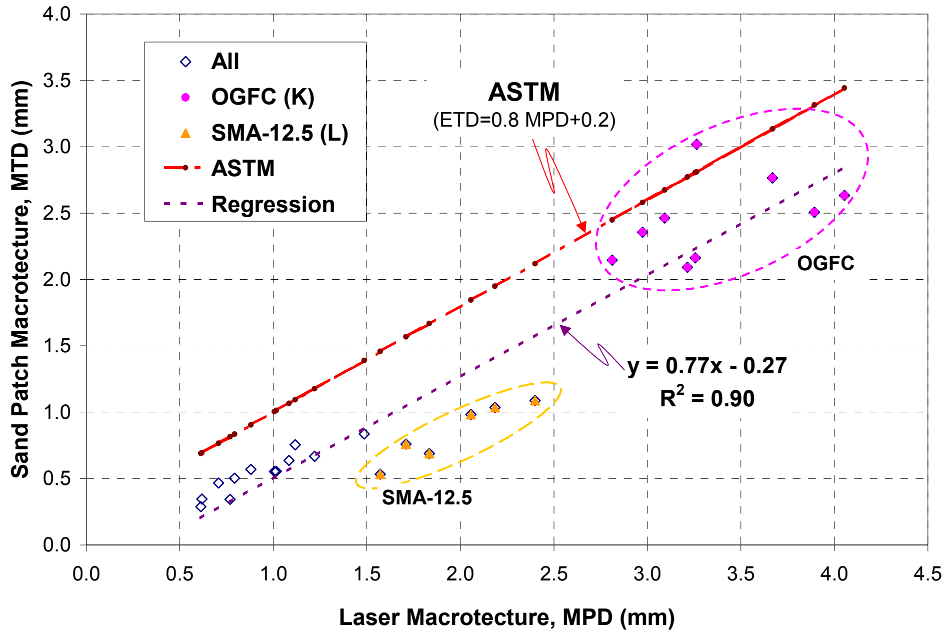

FIGURE 4 Correlation among Sand Patch and Laser Macrotexture Measurements.

DATA ANALYSIS AND DISCUSSION

The impact of the different testing conditions on the skid number of the surface mixtures was studied using an analysis of variance on the entire test data measured at 64 ± 2.4 km/hr. Tests were divided into three groups according to the test date. Each consisted of a test performed using a bald tire and a test using the ribbed tire. The ANOVA shown in Table 4 lists the results of analysis of the skid data.

TABLE 4 ANOVA

Source	DF	ANOVA SS	Mean Square	F Value	p_r>F
Model	16	70250	4390.6	117.5	<0.0001
Tire Type[(1)]	1	39834	39833.2	1066.4	<0.0001
Lane[(2)]	1	880	880.3	23.6	<0.0001
Grade[(3)]	1	19	18.6	0.5	0.4811
Test[(4)]	2	20645	10322.3	276.3	<0.0001
Section[(5)]	11	8873	806.6	21.6	<0.0001
Error	744	27792	37.4		
Corrected Total	760	98042			

(1) Tire type: smooth, ribbed,
(2) Lane: instrumented, non-instrumented
(3) Grade: uphill, downhill
(4) Test: March 00, Sep.-Oct 00, Feb. 01
(5) Section: A through L

As expected, the analysis indicates that the tire type and test date are highly significant. There are also significant differences among sections and lanes, and thus among mixes. On the other hand, the effect of grade (uphill/ downhill) was insignificant in the model. The incidence of the significant factors is further discussed in the following sections of the paper.

Effect of Tire Type and Time in Service

Further analysis confirmed that the skid resistance measurements were highly dependent on the type of tire used for the measurements. Figure 5 shows the skid numbers measured at 64 km/h for different test dates for both smooth (SN_S) and ribbed tires (SN_R). It can be observed that for the finer mixtures (9.5mm NMS), the skid numbers from the ribbed tire after some time in service, are higher than those taken from the smooth tire. Coarser mixtures initially appeared to have lower SN_R than the standard 9.5mm NMS mixes but comparable SN_S. However, there seems to be a tendency of increased SN_R with time, probably due to weathering of the asphalt film.

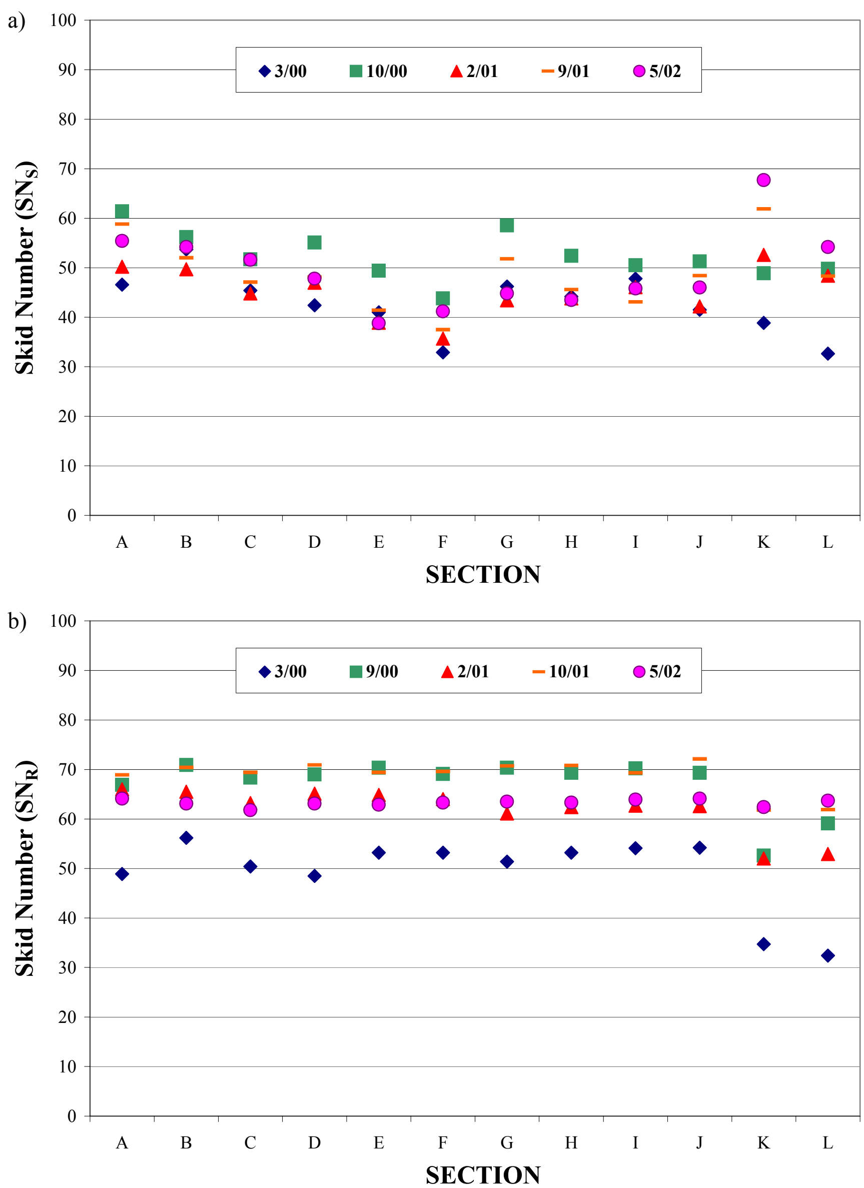

FIGURE 5 Skid Number Measurements Changes with Time.

Figure 5 also shows that skid measurements conducted using the smooth tire increase with time, followed by a decrease to initial levels of skid resistance. The ribbed tire measurements increase dramatically between the first two tests, followed by a small decrease. The fluctuation of the skid numbers recorded by the two tires with time is thought to be caused by changes in macrotexture and microtexture (not measured in this study) and/or changes in temperature and cleanness of the surface during testing.

Variation of Skid Number with Speed

Previous research indicates that the skid number is highly dependent upon the test speed (*17*). To determine the effect of speed on the skid resistance of the different mixtures, linear and exponential regression models were fitted to the skid resistance measurements from all of the test dates (Figure 6). The exponential regression followed the form of the PSU(1) model (*18*), which is as follows:

$$SN = SN_0 e^{(-\frac{PNG}{100} * v)} \tag{5}$$

where,
SN = calculated skid number;
SN_0 = skid number at zero speed (indicator of microtexture);
PNG = percent normalized gradient (indicator of macrotexture); and
V = velocity in mi/h.

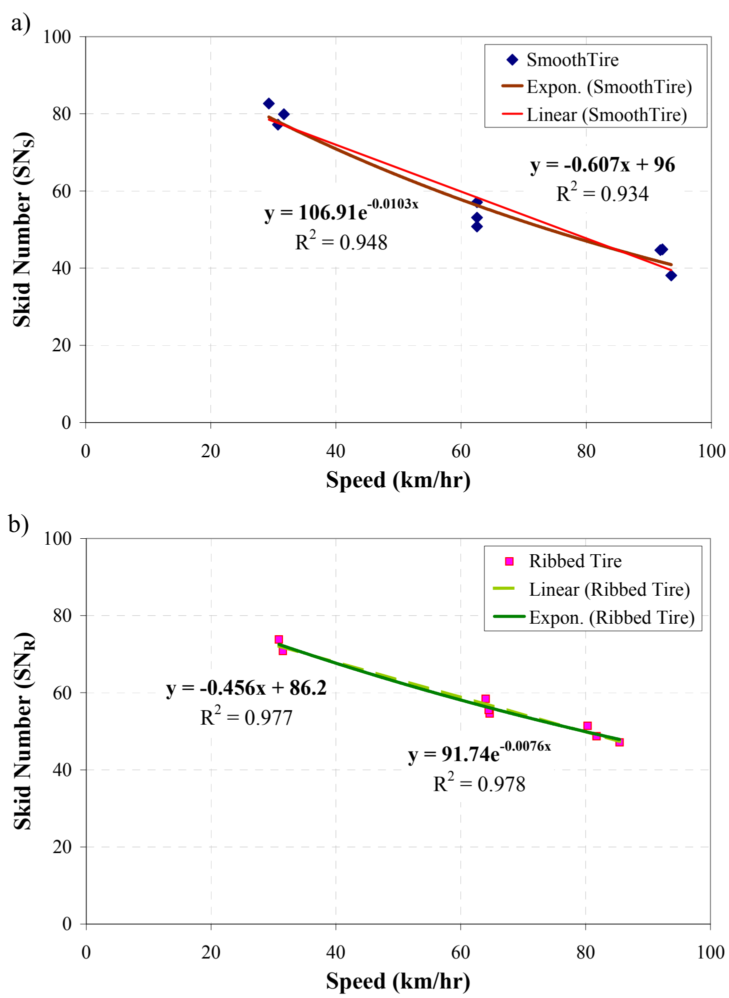

FIGURE 6 Comparison of Linear and Exponential SN / Speed Models.

The comparison of the regressed PSU(1) and linear equations showed that both models adequately fit the experimental data. The average coefficient of determination for all of the experimental data was similar for both models (R^2 =0.905 for the linear equation and R^2 = 0.898 for the PSU(1) model). Therefore, the exponential model was used.

Changes in the percent normalized gradient (determined from the experimental data using regression analysis) with time are presented in Figure 7. It can be observed that the OGFC has the lowest speed-skid number relationship of all of the mixtures, indicating that it has the least skid resistance dependence on speed, which is to be expected with this type of mixture. In addition, it also depicts a noticeable difference in speed dependency between the two tires. Measurements conducted using the smooth tire show a higher dependency on speed than measurements taken with the ribbed tire. Furthermore, Figure 7 shows oscillations in the PNG with time, which can be due to seasonal variations.

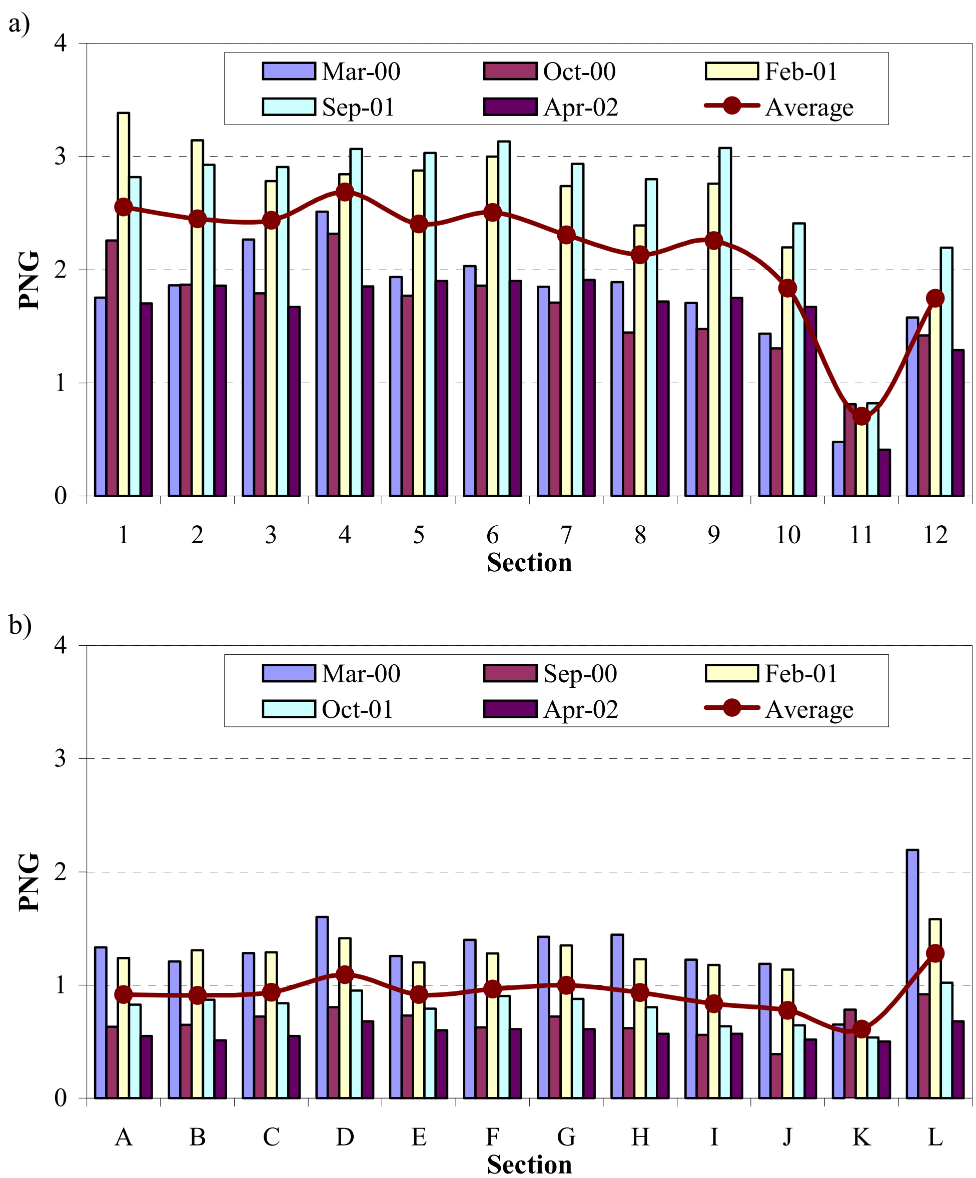

FIGURE 7 Variation of the Average Percent Normalized Gradient over Time (a) Smooth Tire, (b) Ribbed Tire.

Effect of Material Properties

It has been established that good microtexture is important at low speeds and good macrotexture is important at high speeds (*19*). The macrotexture of the pavement is said to provide the hysteresis component of skid resistance (*20*). However, some researchers believe that the microtexture of the aggregate is important not only for low speed skid resistance but for high speed skid resistance as well. Studies suggest that while good vehicle tires can compensate for inadequate macrotexture, low levels of microtexture cannot be compensated for (*21*).

Past studies demonstrated that the aggregate type and structure significantly influence microtexture and macrotexture, and thus skid resistance of a paved surface (*22*, *23*, *24*, *25*, *26*, *27*). Other HMA properties, such as asphalt content and void content, also affect skid resistance.

The impact of laboratory determined HMA design properties on the different wearing surface parameters was studied using regression analysis. Parameters included in the study are the $SN(64)_R$, $SN(64)_S$, and MPD. SAS statistical software was used to conduct a stepwise regression analysis to evaluate the relationship between the mixture properties presented in Table 2 and the pavement surface characteristics. The model with the best statistics was selected for each surface parameter. To minimize the variability due to testing conditions, only the measurements conducted on February 7, 2001 using the smooth and bald tires were used for the analysis. These values reflect the “in-service” skid numbers of the pavement after initial wearing has occurred due to sixteen-months of research traffic.

SN(64) Analysis

Analysis of the skid number at 64 km/hr as measured using the ribbed and smooth treaded tires resulted in the following equation:

$$SN(64)_S = 26.865 + 2.079 * Binder + 1.601 * PP200 + 1.03 * VTM \quad (6)$$

where,
Binder = binder code (-1 for PG 64-22, 0 for PG 70-22, and 1 for PG 76-22);
PP200 = percentage of material passing the #200 sieve (mm); and
VTM = total voids in the mixture.

Although this equation can only explain 23 percent of the variability in the data ($R^2 = 0.231$) and the mean root squared error is high (RMSE=6.7), the variables incorporated into the model are reasonable. An increase in voids in the mixture increases the $SN_{(64)S}$ because it allows water to flow from the tire-pavement interface. The increase in the percentage passing the number 200 sieve increases the exposed microtexture and the positive binder type coefficient indicates an increase in SN with polymerized binders.

Analysis performed using the ribbed tire SN measurements resulted in the regressed equation shown below:

$$SN(64)_R = 104.211 - 4.356 * NMS + 0.1833 * VTM \quad (7)$$

where,
NMS = nominal maximum size (mm).

The coefficient of determination for this equation was 0.768 and the RMSE was 2.45, indicating a much better fit to the experimental data than the smooth tire measurements. Again, the variables incorporated into the equation are logical in terms of past knowledge concerning SN_R, which is affected mostly by the microtexture in contact with the tire. Larger aggregate (represented by the NMS variable) may reduce the amount of contact the tire has with the small asperities of the aggregate surface. As in the previous case, an increase in voids contributes to enhanced skid resistance by reducing the amount of water at the pavement surface and enhancing the contact between pavement and tire.

Mean Profile Depth Analysis

The regression analysis of the laser mean profile depth measurements indicated that, for the range of mixes studied, MPD can be predicted using NMS and VMA. The resulting equation, with an R^2 value of 0.965 and RMSE=0.123, is the following:

$$MPD = -2.896 + 0.2993 * NMS + 0.0698 * VMA \quad (8)$$

where,
VMA = voids in the mineral aggregate (%).

The inclusion of these variables is logical because of increases in aggregate size and VMA results in coarser macrotexture.

International Friction Index

The Sp, which is calculated based on the texture properties of the surface, resulted in a similar equation to the MPD. The Sp equation (R^2 = 0.965, RMSE = 12.40) is as follows:

$$Sp = -270.0 + 28.3 * NMS + 6.79 * VMA \quad (9)$$

Although F60 is a linear combination of the other parameters, a regression equation was obtained for this parameter. The equation that best represent the impact of specific properties on the F60 parameter (R^2 = 0.412, RMSE = 0.048) is shown below:

$$F60 = 0.38189 - 0.02962 * Tire + 0.01295 * Binder + 0.00911 * PP200 + 0.00897 * VTM \quad (10)$$

where,
Tire = type of tire used in the testing (0, 1).

The variables Tire and VTM were found to be significant to the 0.001 level, indicating that they are the major contributors to the F60 of those included in the analysis. The friction increases with increased voids and percentage passing 200, as well as with the use of modified binders. Regression performed with the ribbed and smooth tire data separately showed a better fit to the material properties with the ribbed tire F60 than the smooth tire F60. The F60 values for the 12 Smart Road experimental sections computed based on the 64 km/hr are presented in Figure 8. The figure shows that the F60 computed using the smooth and ribbed tires were not consistent for all mixes.

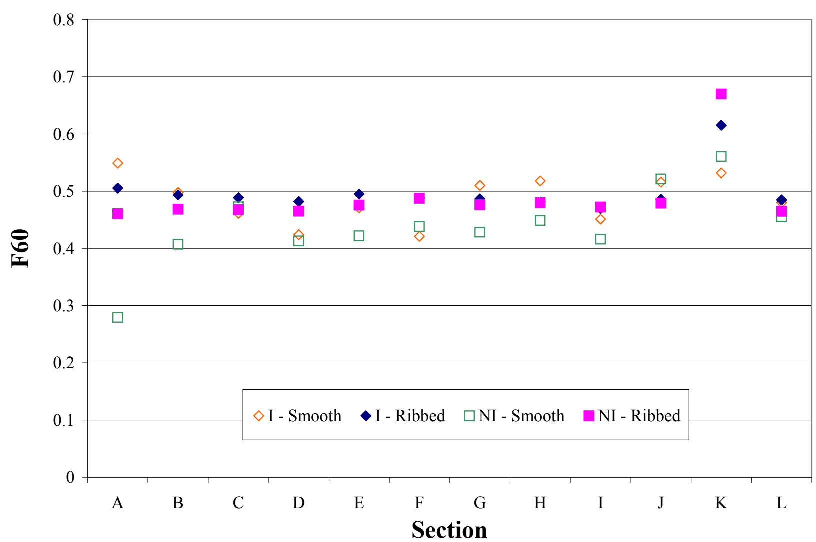

FIGURE 8 IFI F60 Computed using the Smooth and Ribbed Tires.

SUMMARY AND CONCLUSIONS

This paper discussed the surface characteristics of seven different HMA surface mixtures used at the Virginia Smart Road. Variations in measurements due to testing conditions such as tire, speed, grade, and their relationship to HMA characteristics were analyzed. The seven HMA surface mixtures include five different SuperPave^{TM} mixes, a stone mastic asphalt (SMA), and an open-graded friction coarse (OGFC). Mixture properties were measured from samples taken from each section during construction.

The evaluation of the surface characteristics included skid resistance using a locked-wheel trailer (both lanes, different speeds, uphill and downhill, with smooth and ribbed tires) and surface macrotexture using a laser device (both lanes). Statistical tests indicate that, for the mixes studied, the roadway grade has insignificant effect on the skid number measurements. Friction measurements, however, are dependent on surface texture, age in service, and temperature of the surface.

The relationship between skid number and speed can be appropriately modeled using both exponential (Penn State model) and linear models. The dependence of skid numbers on the measurement speed changes with time, testing conditions, and tire type. As expected, the OGFC is the least influenced by measuring speed among all mixes.

Some of the frictional properties of the wearing surface mixes can be predicted based on HMA design properties. For the range of mixes studied, MPD can be closely predicted based on the NMS and VMA. Furthermore, $SN_{(64)R}$ is mostly influenced by the NMS and VTM. The greater the NMS, the lower the ribbed tire SN. Other aggregate parameters (such as angularity and coefficient of uniformity) and mixture properties have to be considered to accurately predict $SN_{(64)S}$. The computed normalized wet friction values at 60 km/hr (F60) for the smooth and ribbed tires were not consistent for all mixes.

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REFERENCES

(1) Smith, K.L., Smith, K.D., Evans, L.D., Hoerner, T.E., Darter, M.I., and Woodstrom, J.H. (1977). *Smoothness specifications for pavements*. National Cooperative Highway Research Program 1-31, unpublished report.

(2) McGhee, K.K. (1999). *Measuring, achieving, and promoting smoothness of Virginia's asphalt overlays*. Virginia Transportation Research Council Research Report, Charlottesville, VA.

(3) Smith, Harry (1976). Pavement contributions to wet-weather skidding accident reduction. *Transportation Research Record, 622*, 51-59.

(4) Panagouli, O.K. and Kokkalis, A.B. (1998). Skid resistance and fractal structure of pavement surface. *Chaos Solutions and Fractals*, *9* (3), 493-505.

(5) Haas, R., Hudson, R.W., and Zaniewski, J. (1994). *Modern pavement management*. Florida: Krieger Publishing Company.

(6) Tighe, S, Li, N, Falls, LC, Haas, R. (2000). Incorporating road safety into pavement management. *Transportation Research Record*, *1669*.

(7) Ivey, D.L., Griffin, L.I. III, Lock, JR, and Bullard, D.L. (1992). *Texas skid initiated accident reduction program. Final Report.* Research Report 910-1F, TTI: 2-18-89/910, TX-92/910-1F, Texas Department of Transportation, Austin, TX.

(8) Ivey, D.L. and w. Frank McFarland (1981). Economic factors related to raising levels of skid resistance and texture. *Transportation Research Record, 836*, 83-86.

(9) Henry, J.J. (2000). *NCHRP Synthesis291, evaluation of pavement friction characteristics*, National Cooperative Highway Research Program, Transportation Research Board, Washington, DC.

(10) Alsopp, H.C. (1985). Road surface friction measurements, methods, and machines. *Anti-Lock Braking Systems for Road Vehicles*. Institution of Mechanical Engineers. London: Mechanical Engineering Publications Limited, 61-72

(11) American Society for Testing and Materials. (1998). *Annual book of ASTM standards.* Volume 04.03: 669-673, 682-684, 690-692.

(12) Wambold, J.C., Antle, C.E., Henry, J.J., and Rado, Z. (1995). *International PIARC Experiment to Compare and Harmonize Texture and Skid Resistance Measurements*. Permanent International Association of Road Congresses.

(13) Leu, M. C. and Henry, J.J. (1983). Prediction of skid resistance as a function of speed from pavement texture. *Transportation Research Record, 946*.

(14) Al-Qadi, I.L., Nassar, W.M., Loulizi, A., Flintsch, G.W., and Freeman T.E. (2000, January). Flexible pavement instrumentation at the Virginia Smart Road. *Transportation Research Board 79th Annual Meeting*. Washington, DC: preprint 00-1275.

(15) Virginia Department of Transportation. (1999). *Special provision for section 211 asphalt concrete mixtures (SUPERPAVE)*. Richmond, VA.

(16) Takino, H., Isobe, N., Tobori, H. and Kohjiya, S. (1998). Effect of cohesion loss factor on wet skid resistance of tread rubber. *Tire Science and Technology*, TSTCA, *26*(4), 258-276.

(17) Wambold, J.C. (1988). Obtaining the skid number at any speed from a test at single speed. *Transportation Research Record*, *1196*, 300-305.

(18) Henry, J.J. and Saito, K. (1983). Skid resistance measurements with blank and ribbed test tires and their relationship to pavement texture. *Transportation Research Record*, *946*, 38-43.

(19) AASHTO Task Force for Pavement Design. (1976). *Guidelines for skid resistant pavement design*. The American Association of State Highway and Transportation Officials.

(20) Forster, S.W. (1989). Pavement microtexture and its relation to skid resistance. *Transportation Research Record*, *1215*, 151-164.

(21) Dupont, P. and Ganga, Y. (1995, September). Skid resistance and texture measurement of road surfaces on difficult sites. Paper presented at the *XXth World Road Conference,* Montreal, Canada.

(22) Britton, S.C., Ledbetter, W.B., and Gallaway, B.M. (1974, March). Estimation of skid numbers from surface texture parameters in the rational design of standard reference pavements for test equipment calibrations*.* *Journal of Testing and Evaluation*, *2* (2), 73-83.

(23) Beaton, J.L. (1976). Providing skid resistant pavements. *Transportation Research Record*, *622*, 39-50.

(24) Henry, J.J. and Dahir, S.H. (1979). Effects of textures and the aggregates that produce them on the performance of bituminous surfaces. *Transportation Research Record, 712*, 44-50.

(25) Baran, R.G. and Henry, J.J., (1983). Tire noise and its relation to pavement friction. *Transportation Research Record, 946*, 44-48.

(26) Forster, S.W. (1989). Pavement microtexture and its relation to skid resistance. *Transportation Research Record, 1215*, 151-164.

(27) Kandhal, P.S. and Frazier P. Jr. (1998). *Aggregate tests related to asphalt concrete performance in pavements*. NCHRP Report 405, National Academy Press, Washington, D.C.