Pavement Surface Macrotexture Measurement and Application

Gerardo W. Flintsch
Assistant Professor, The Via Department of Civil and Environmental Engineering
Transportation Fellow, Virginia Tech Transportation Institute
200 Patton Hall, Virginia Polytechnic Institute and State University
Blacksburg, VA 24061-0105
voice (540) 231 9748, fax (540) 231 7532
email: flintsch@vt.edu

Edgar de León
Graduate Research Assistant, Virginia Tech Transportation Institute
3500 Transportation Research Plaza
Blacksburg, VA 24061-0105
voice (540) 231 1568, fax (540) 231 1555
email: edeleoni@vt.edu

Kevin K. McGhee
Senior Research Scientist, Virginia Transportation Research Council
530 Edgemont Road
Charlottesville, VA 22903
voice (434) 293-1956, fax (434) 293-1990
email: McGheeKK@vdot.state.va.us

Imad L. Al-Qadi
Charles E. Via, Jr., Professor of Civil and Environmental Engineering
Leader, Roadway Infrastructure Group, Virginia Tech Transportation Institute
200 Patton Hall, Virginia Polytechnic Institute and State University
Blacksburg, VA 24061-0105
voice (540) 231 5262, fax (540) 231 7532
email: alqadi@vt.edu

Virginia Tech Transportation Institute
Virginia Tech
Blacksburg, VA
Pavement Surface Macrotexture Measurement and Application

ABSTRACT

This paper discusses different techniques for measuring pavement surface macrotexture and its application in pavement management. The main applications of surface macrotexture are to measure the frictional properties of the pavement surface and to detect hot mix asphalt (HMA) construction segregation or non-uniformity. Since surface macrotexture can be measured quite efficiently using non-contact technologies and provides important information regarding pavement safety and HMA construction quality, this parameter may be included in the quality assurance or control procedures.

Correlations between different measuring devices were investigated utilizing different HMA wearing surfaces. Excellent correlation was found between the CTMeter and the sand patch measurements. In addition, the Mean Profile Depth (determined using a laser profiler) correlates well with the sand patch measurements.

Consistent with previous studies, it was found that the skid number gradient with speed is inversely proportional to the pavement macrotexture. However, there was a noticeable difference in speed dependency when using the smooth and ribbed tires and oscillations in the percent normalized gradient with time due to seasonal variations were observed.

Macrotexture measurements hold great promise as tools to detect and quantify segregation for quality assurance purposes. A standard construction specification has been proposed in a recent NCHRP study. However, the equation proposed for computing the non-segregated ETD could not be applied to the mixes studied. An alternative equation has been proposed, which estimates the surface macrotexture using the mix nominal maximum size and voids in the mineral aggregate. Further investigation using other mixes than the ones used at the Virginia Smart Road is recommended.
INTRODUCTION

The current trend towards mechanistic flexible pavement design and analysis procedures has placed a great deal of emphasis on intergraded pavement and hot-mix-asphalt (HMA) systems design. Within this scheme, HMA is designed to be strong and resilient to withstand traffic and environmental conditions expected for a particular roadway section over its design life. Traditional HMA construction quality control and assurance procedures reflect this approach and focus on ensuring the required strength and durability of the material.

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, especially for the wearing surface mixes. Construction specifications for smoothness have been implemented by several states (1, 2). HMA safety-related texture and skid properties are not yet quantitatively included in most specifications. Since surface macrotexture can be measured quite efficiently using non-contact technologies and since it provides important information regarding pavement safety and HMA construction quality (uniformity), this parameter could be efficiently included in the quality control procedures.

Several authors have discussed the incorporation of pavement-related safety considerations into the pavement management process. Tighe et al. (3) identified the main pavement engineering relationships associated with road safety and related to pavement management. 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. The two most promising applications of surface macrotexture measurements include pavement safety assessment and segregation detection.

Surface macrotexture is a predominant contributor to wet-pavement safety (4, 5). The safety of a pavement surface is related to both the surface friction and texture of the pavement. It is imperative that pavement surfaces provide adequate friction and drainage ability to minimize the number of accidents that occur as a result of frictional deficiencies. These frictional properties of pavement surfaces are determined by the surface condition (porosity, wear, etc.), HMA properties (aggregate type and gradation), and environmental conditions (6, 7). Designing and maintaining HMA wearing surfaces that provide adequate skid resistance and texture may decrease wet weather accidents.

Continuous macrotexture measurements can also be used to detect HMA construction segregation or non-uniformity (8). Traditionally, visually identified areas of non-uniform surface texture have been subjectively classified as segregated mix and, consequently, bad construction. This has caused disputes between contractors and highway agencies. Many studies have attempted to develop reliable and independent methods to define, detect, and quantify segregation, but none have eliminated the need for visual inspections prior to measuring the identified areas. An objective quantitative macrotexture-based method has been proposed (8).

This paper discusses the different techniques for measuring pavement surface macrotexture and its application in pavement management. It also presents correlations between different macrotexture measuring devices determined using different HMA wearing surfaces at the Virginia Smart Road. The effect of macrotexture on skid resistance and the possibility of predicting “non-segregated” macrotexture based on HMA design and production properties are investigated.

PAVEMENT SURFACE TEXTURE

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 is important in the design of a pavement wearing surface.
Pavement texture is the feature of the road surface that ultimately determines most tire-road interactions such as 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 as roughness, smoothness, or evenness (9).

The resistance to skidding on a road surface is largely affected by both microtexture and macrotexture. Figure 1 illustrates the concept of microtexture and macrotexture. Pavement macrotexture provides the hysteresis component of the friction and allows for the rapid drainage of water from the pavement. The enhanced drainage improves the contact between the tire and the pavement surface and helps reduce the probability of hydroplaning. Microtexture provides direct tire-pavement contact and contributes to the adhesion component of the friction (9).

Increasing the texture of in-service or new pavement surfaces would increase the skid resistance levels of the pavement. This may sometimes increase the level of discomfort for vehicle occupants and adjacent property owners because of increased interior and exterior noise, vibration, fuel consumption, and tire wear (10). However, the negative aspects of increasing pavement friction are outweighed by the potential decrease in the number of accidents due to inadequate pavement friction (11).

**Macrotexture**

The macrotexture of a pavement surface results from the large aggregate particles in the mixture. A detailed list of different devices currently in use for measuring pavement surface texture is provided elsewhere (9). 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 (12), is a volumetric approach of measuring pavement macrotexture. A known volume of sand (or glass beads) 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). Because of operator dependency, the test results have poor repeatability (9). However, since there is great deal of past research, this volumetric test is still used as the reference “ground-truth” standard throughout the word.

The outflow meter indirectly estimates 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 with a 142mm radius and measures the texture with a sampling interval of approximately 0.9mm.

Vehicle-mounted laser devices are typically used to measure macrotexture without disrupting traffic flow. A standard method for determining the Mean Profile Depth (MPD) of the pavement macrotexture from a pavement profile is provided in ASTM Standard E1845 (12). The MPD is a two-dimensional estimate of the three-dimensional MTD. Some equipment manufacturers also use the Root Mean Square (RMS) of the profile after filtering to remove wavelengths longer than 100mm. However, area-based measures, such as the MPD, correlate better with the volumetric patch method and with friction (13).

According to ASTM E1845 (12), 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 for each half segment and the average of both halves computed. The average peak value of both segments is reported as MPD (Figure 2). When MPD is used to estimate the MTD by means of a transformation equation, the computed value is called Estimated (mean) Texture Depth (ETD).
Microtexture Measurements

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

MACROTEXTURE MEASUREMENTS CORRELATION

Two laser macrotexture measuring devices owned by the Virginia Transportation Research Council (VTRC) were compared and referenced to ground-truth sand patch tests. The laser devices evaluated include a CTMeter (manufactured by Sunny Kenko) and a laser inertial road profiler (manufactured by the International Cybernetics Corporation, ICC).

All the measurements were conducted at the Virginia Smart Road, which is a controlled traffic facility with seven different HMA wearing surfaces. These wearing surfaces include different SuperPave™ mixtures, a 12.5mm stone mastic asphalt (SMA), and a 12.5mm open-graded friction course (OGFC). Limited tests were also conducted on a texturized, continuously reinforced concrete section. Measurements were taken the same day at three locations within each section studied on both the left wheel path and in-between wheel paths. The profiler was run three times for each lane and the average MPD for a 1.5m (5ft) section centered on the selected location was used for the comparisons. The average of the three runs was used to partially compensate for lateral variability. The sand patch tests (using Ottawa sand) were conducted after the CTMeter measurements in the same location.

CTMeter vs. Sand Patch Correlation

The correlation between the CTMeter and the sand patch measurements was excellent, as shown in Figure 3. Using all points, an almost one-to-one relationship was obtained with a coefficient of determination ($R^2$) of 0.943. These results are consistent with those reported elsewhere, and indicate that the sand patch test can be substituted by the more objective CTMeter test with a high degree of accuracy.

Laser Profiler vs. Sand Patch Correlation

Figures 4a and 4b compare the measurements taken with the laser profiler to those taken with the sand patch tests. Both linear and exponential regression equations are superimposed to the experimental data. The linear equation indicates a slightly weaker correlation ($R^2=0.884$) than in the case of the CTMeter. Figure 4a indicates that the relationship may be different from the one used by ASTM E-1845, which is given by Equation 1:

$$ETD = 0.2 + 0.8MPD$$

Equation 1 is formed by rounding the relationship obtained from comparing the equations used in the International Friction Index (IFI; $I_2$, $I_4$) to compute the speed constant ($Sp$). Equation 2 is obtained by combining the $Sp$ equations using MPD and MTD:

$$ETD = 0.227 + 0.79MPD$$

The relationship obtained in this study is roughly parallel to that used in ASTM E-1845, which may indicate a possible bias in the laser profiler used for this investigation. The discrepancy could also be due to possible differences in the algorithm used to compute the MPD between the profiler used for this study and that used in ASTM E-1845. Furthermore, some researchers believe that macrotexture...
measurements on open graded surfaces are questionable because the laser profiler cannot detect some of the voids that are filled with sand. The placement on the chart of the different surfaces studied is displayed graphically in Figure 4b.

EFFECT OF PAVEMENT MACROTEXTURE ON SKID RESISTANCE

The effect of pavement texture on pavement skid resistance has been reported in early skid resistance studies (17, 18, 19). The complete frictional characteristics of the road can be found if both the microtexture and macrotexture are known. Early on it was established that good microtexture is important at low speeds and good macrotexture is important at high speeds (20). However, some researchers believe that the microtexture of the aggregate is important at all speeds (21). The effect of texture on water drainage into the pavement tire contact and its effect on skid resistance and hydroplaning are discussed elsewhere (22).

International Friction Index

The recently proposed IFI formally incorporates pavement macrotexture. The IFI was developed as a common reference scale for quantifying the pavement surface frictional properties (14). To calculate the IFI, it is necessary to have at least one friction measurement and one macrotexture measurement (12). The IFI is reported in two parameters: the normalized wet friction value at 60 km/hr (F60) and a speed constant (S_p). A transformation equation has also been established to allow for calculation of the wet friction value at speeds other than 60 km/hr.

The importance of good macrotexture is depicted in Figure 5. In addition to reducing the chances of hydroplaning (23), high macrotexture reduces the gradient of skid resistance with speed, thus improving skid resistance at high speeds. This implies that the gradient is inversely proportional to the pavement macrotexture. Previous research indicates that the skid number is highly dependent upon the test speed (15, 24, 25) following the exponential model known as the Penn State Model (PSU (1)), which is given by Equation 3:

\[ SN = SN_0 * e^{\left(\frac{PNG}{100}v\right)} \]  

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.

Equation 3 was used for developing the IFI speed correction formula, in which the term PNG was substituted by 100/S_p. Thus, the speed constant, S_p, which depicts the change of friction with speed, is proportional to macrotexture and can be computed using Equation 4:

\[ S_p = a + b * TX \]  

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

If the measurements are conducted using a ribbed tire, which is relatively insensitive to macrotexture properties of the surface (14), then the macrotexture measurement is also used to correct the normalized wet friction value at 60 km/hr (F60). The adjusted friction value and the texture measurement are used to calculate the value for F60 using Equation 6:

\[ F60 = A + B \times FR60 + C \times TX \]  

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 5; and
TX = Macrotexture measurement (mm).

IFI Speed Constant Equation Validation

The validity of the relationships between skid number speed gradient and macrotexture was investigated using friction and texture measurements. These tests were conducted over a three-year period on the seven HMA mixes at the Virginia Smart Road. The effect of testing condition on the relationship was also investigated. The average macrotexture (ICC MPD) of each section was recorded at quarterly intervals. Measurements were obtained on the left wheelpath (LWP) and in-between wheelpaths (BWP). The MPD measurements for all sections throughout the study period are shown in Figure 6. It can be observed that the measurements did not vary significantly over time. The first set of test data was excluded from the following analysis because of some difficulty in distinguishing section breaks in the measurement data.

Skid resistance testing of the different surfaces was also periodically performed on both lanes in both directions. Both ASTM standard tires (ribbed and smooth) were used. Tests were performed at three speeds (32, 64, and 80km/hr). Three replicates in each lane and direction were used for each tire. An exponential model (PSU (1)) was determined using regression analysis for each section, lane, direction, and testing date. The coefficient of determination was very good for almost all tests; the average \( R^2 \) considering all of the experimental data was approximately 0.90.

Changes in the percent normalized gradient (determined using regression analysis) with time are presented in Figure 7. There is 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 are believed to be due to seasonal variations. This hypothesis is currently being investigated.

Figure 8 shows the measured and computed SN: speed gradients for the Virginia Smart Road HMA mixes. The Figure suggests that the coefficients used to compute \( S_p \) based on MPD measurements may not be applicable to the equipment and mixes considered in the study. The lack of agreement could be due to the algorithm used to compute the MPD utilized by the profiler or to the types of mixes.
considered. The profiler used in this study may not have provided a standard MPD value according to ASTM E-1845. Furthermore, the experimental $S_p$ is not consistent for the smooth and ribbed tires.

**USE OF MACROTERRAIN FOR HMA SEGREGATION DETECTION AND MEASUREMENT**

The use of macrotexture measurements as a mean to detect and measure HMA construction segregation has been proposed in a National Cooperative Highway Research Program (NCHRP) study (8). Segregation may be defined as a lack of homogeneity (uniformity) in the HMA constituents of the in-place mat of such magnitude that there is reasonable expectation of accelerated pavement distress(es). A segregated mix does not conform to the original job mix formula (JMF) in gradation and/or asphalt content, which also creates a difference in the expected density and air void content of the mix. Research has shown that when this happens, there is a loss of pavement service life because of diminished stiffness, tensile strength, and fatigue properties, which all result in accelerated pavement distresses such as raveling, longitudinal cracking, fatigue cracking, and rutting (8, 26, 27, 28).

The aforementioned study (8) investigated available technologies for detecting segregation (visual identification, sand patch, and nuclear density gauges) and measuring segregation (permeability, nuclear density/moisture content gauges, and destructive testing). Many developing technologies were also evaluated such as infrared thermography, ground penetration radar (GPR), thin-lift nuclear asphalt content/density gauges, laser surface texture measurement devices, and seismic pavement analyzers. The criteria used to evaluate the methods and technologies included the ability to measure and detect mixture properties that would change because of segregation, and the availability of equipment that can be used in a rapid, repeatable, and nondestructive manner preferably at normal highway speed. The study recommended infrared thermography and laser surface texture measurements as the most promising technologies. A draft construction specification designed to identify and measure segregation was proposed.

Further evaluation of these technologies suggested that infrared thermography has good potential for quality control purposes because it can be used during paving operations. On the other hand, laser profiling appears to be the most practical mean for detecting and quantifying segregation for quality assurance purposes. Based on the information available about ongoing research at the time of preparing the paper, there are at least four State DOTs (Kansas, New Jersey, Texas, and Virginia) that are considering the use of laser profiling for segregation detection and measurement. However, before judgments regarding the varying degrees of segregation can be made, an objective estimate of non-segregated texture is first required.

**Non-Segregated Macrotessure Determination Based on HMA Design Properties**

Past studies demonstrated that aggregate type and structure significantly influence microtexture and macrotexture (29). Other HMA properties, such as asphalt content and void content, also affect macrotexture. A model for predicting the ETD (estimate of the MTD computed using ROSAN laser measurements) using wearing surface mix properties has been proposed. The model was developed based on a limited assortment of HMA mixes. According to the study, the non-segregated ETD of a HMA could be computed based on Equation 7 (8):

$$ETD = 0.01980 * MS - 0.004984 * P4.75 + 0.1038 * C_c - 0.004861 * C_u$$

where,

- $MS =$ maximum size of the aggregate (mm);
- $P4.75 =$ Percentage passing 4.75mm sieve;
- $C_c =$ coefficient of curvature = $(D_{50})^2/(D_{10}D_{60})$;
- $C_u =$ coefficient of uniformity = $D_{60}/D_{10}$;
- $D_{10} =$ the sieve size associated with 10% passing (mm);
$D_{30}$ = the sieve size associated with 30% passing (mm); and
$D_{60}$ = the sieve size associated with 60% passing (mm).

The values computed based on the measured mix properties for some of the HMA mixes studied are compared with the corresponding average sand patch measurements in Figure 9. The average mix properties obtained from field cores are presented in Table 2. The data in Figure 9 suggest that the equation cannot appropriately predict the macrotexture for the mixes studied (especially for the SMA and OGFC mixes). No visual segregation was detected in any of the mixes.

A study of the Virginia Smart Road mixes also investigated the possibility of predicting non-segregated field macrotexture based on mix properties determined on laboratory-compacted specimens. Loose samples were taken during placement of the wearing surface from which specimens were prepared in the laboratory in accordance with the Virginia Department of Transportation (VDOT) mixture design practices. This study concluded that the surface macrotexture could be predicted using the aggregate nominal maximum size (NMS) and voids in the mineral aggregate (VMA). The study resulted in the regression Equation 8 to compute an estimated ICC MPD (or EPD). The model had an $R^2$ value of 0.965 and a root mean squared error (RMSE) of 0.123mm.

$$EPD = -2.896 + 0.2993 * NMS + 0.0698 * VMA$$

where,
NMS = nominal maximum size (mm); and
VMA = voids in the mineral aggregate (%).

A continuation of this study is currently looking into adjusting the equation to use actual “as-constructed” mix properties determined for the same mixes from cores extracted from the pavement soon after construction. A validation effort using a wider range of mixes and locations is also underway.

SUMMARY AND CONCLUSIONS
The main applications of surface macrotexture for pavement management are to measure the frictional properties of the pavement surface and to detect HMA construction segregation or non-uniformity. Since surface macrotexture can be measured quite efficiently using non-contact technologies and can provide important information regarding pavement safety and HMA construction quality, this parameter may be included in the quality assurance or control procedures.

Correlations among different macrotexture measuring methods and devices were investigated based on measurements determined from seven different HMA wearing surfaces. The correlation between the CTMeter and the sand patch measurements was excellent ($R^2=0.94$). The correlation between the MPD (determined using a profiler) and the sand patch was also strong ($R^2=0.88$). However, the developed relationship obtained is not in agreement with the one presented in ASTM E-1845. This suggest a possible bias in the laser profiler used for this investigation, or a difference in the algorithm used to compute the MPD.

Consistent with previous studies, it was found that the skid number gradient with speed is inversely proportional to the pavement macrotexture. In addition, there was a noticeable difference in speed dependency when using the smooth and ribbed tires. Measurements conducted using the smooth tire showed a higher dependency on speed than those measurements taken with the ribbed tire. Oscillations in the PNG with time due to seasonal variations were observed. The analysis suggested that the coefficients used to compute $S_p$ (based on MPD measurements) may not be applicable to the equipment and mixes considered in the study. The lack of agreement could be due to the algorithm used to compute the MPD utilized by the profiler.

Macrotexture measurements hold great promise as tools to detect and quantify segregation for quality assurance purposes. A standard construction specification has been proposed in a recent NCHRP
study; however, the equation proposed for computing the non-segregated ETD could not be applied to the mixes studied. An alternative equation has been proposed, which estimates the surface macrotexture using the mix nominal maximum size (NMS) and voids in the mineral aggregate (VMA). Further investigation using other mixes than the ones used at the Virginia Smart Road is recommended.

AKNOWLEDGEMENTS

The construction and instrumentation of the Virginia Smart Road project has been made possible through a cooperative effort of the Virginia Department of Transportation (VDOT), the Virginia Transportation Research Council (VTRC), Virginia’s Center for Innovative Technologies (CIT), the Federal Highway Administration (FHWA) and Virginia Tech. Special thanks to Robert Honeywell of VDOT; L. E. (Buddy) Wood, Arthur Wagner, Linda De Grasse, and Brian D. Prowell of VTRC; and Amara Loulizi, Mohammad Rahman, Robin Davis, and Jeff Kutesch of Virginia Tech for collaborating in the data collection and analysis.

REFERENCES


LIST OF TABLES AND FIGURES

Table 1. Texture Classifications
Table 2. Laboratory Measured Properties of the Wearing Surface HMA

Figure 1. Microtexture and Macrotecture Illustration
Figure 2. Schematic of Mean Profile Depth Computation
Figure 3. Circular Track Meter and Sand Patch Correlation
Figure 4. Sand Patch and Laser Macrotexture Correlation
Figure 5. Example of Frictional Properties of Surfaces with Various Degrees of Friction and Macrotexture
Figure 6. Mean Profile Depth Measurements for all Sections (a) Instrumented Lane, (b) Non-Instrumented Lane
Figure 7. Variation of the Average Percent Normalized Gradient over Time (a) Smooth Tire, (b) Ribbed Tire
Figure 8. Sp (100/PNG) - Macrotecture Relationship
Figure 9. Measured versus Predicted Macrotecture (NCHRP 441 Model)
### TABLE 1. Texture Classifications

<table>
<thead>
<tr>
<th>Texture Classification</th>
<th>Relative Wavelengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microtexture</td>
<td>$\lambda &lt; 0.5 \text{ mm}$</td>
</tr>
<tr>
<td>Macrotexture</td>
<td>$0.5 \text{ mm} &lt; \lambda &lt; 50 \text{ mm}$</td>
</tr>
<tr>
<td>Megatexture</td>
<td>$50 \text{ mm} &lt; \lambda &lt; 500 \text{ mm}$</td>
</tr>
<tr>
<td>Roughness/Smoothness</td>
<td>$0.5 \text{ m} &lt; \lambda &lt; 50 \text{ m}$</td>
</tr>
</tbody>
</table>
### TABLE 2. Laboratory Measured Properties of the Wearing Surface HMA

<table>
<thead>
<tr>
<th>Section</th>
<th>Mix</th>
<th>Binder</th>
<th>NMS</th>
<th>MS</th>
<th>Pb</th>
<th>PP 9.5</th>
<th>PP 4.75</th>
<th>PP 2.36</th>
<th>PP 1.18</th>
<th>PP 0.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>SM-12.5D</td>
<td>PG 70-22</td>
<td>9.5</td>
<td>12.5</td>
<td>5.9</td>
<td>97.3</td>
<td>81.9</td>
<td>46.0</td>
<td>34.2</td>
<td>26.3</td>
</tr>
<tr>
<td>E-H</td>
<td>SM-9.5D</td>
<td>PG 70-22</td>
<td>9.5</td>
<td>12.5</td>
<td>5.9</td>
<td>93.8</td>
<td>61.6</td>
<td>41.4</td>
<td>29.2</td>
<td>20.1</td>
</tr>
<tr>
<td>J</td>
<td>SM-9.5D</td>
<td>PG 70-22</td>
<td>9.5</td>
<td>12.5</td>
<td>4.9</td>
<td>92.3</td>
<td>53.5</td>
<td>36.5</td>
<td>25.8</td>
<td>18.0</td>
</tr>
<tr>
<td>K</td>
<td>OGFC</td>
<td>PG 76-22</td>
<td>12.5</td>
<td>19</td>
<td>5.5</td>
<td>80.8</td>
<td>13.6</td>
<td>1.8</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>L</td>
<td>SMA-12.5D</td>
<td>PG 70-22</td>
<td>12.5</td>
<td>19</td>
<td>6.8</td>
<td>86.0</td>
<td>36.5</td>
<td>24.6</td>
<td>21.1</td>
<td>18.4</td>
</tr>
</tbody>
</table>
FIGURE 1. Microtexture and Macrotexture Illustration
FIGURE 2. Schematic of Mean Profile Depth Computation
Flintsch, de León, McGhee, and Al-Qadi

\[ y = 0.982x + 0.0364 \]
\[ R^2 = 0.943 \]

**FIGURE 3. Circular Track Meter and Sand Patch Correlation**
FIGURE 4. Sand Patch and Laser Macrotexture Correlation
FIGURE 5. Example of Frictional Properties of Surfaces with Various Degrees of Friction and Macrotexture
FIGURE 6. Mean Profile Depth Measurements for all Sections
(a) Instrumented Lane, (b) Non-Instrumented Lane
FIGURE 7. Variation of the Average Percent Normalized Gradient over Time
(a) Smooth Tire, (b) Ribbed Tire
Smooth Tire
\[ y = 47.8x - 5.5 \]
\[ R^2 = 0.95 \]

Ribbed Tire
\[ y = 20.4x + 84.6 \]
\[ R^2 = 0.39 \]

FIGURE 8. \( S_p (100/PNG) \) - Macrotexture Relationship
FIGURE 9. Measured versus Predicted Macrotexture (NCHRP 441 Model)