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16. Abstract

Skid resistance is an important characteristic of the pavement surface to reduce the number of road accidents. The mechanisms involved in the activation of the frictional force required for a safe braking of the vehicle depend on both the macro- and the micro-texture of the pavement surface. The state-of-the-practice methodologies commonly used for measuring pavement texture at highway speeds only account for the macro-texture, which alone might not be sufficient to effectively characterize skid resistance. This study explored different ways to characterize the micro-texture of pavement surfaces with the main objective of quantifying the effect of accounting for both the micro and the macro components of the texture, rather than just the macro-texture, on the prediction of skid resistance.

The friction and texture data analyzed in this study were collected from an experiment conducted on in-service flexible pavement surfaces. Surface friction was measured using a British Pendulum Tester whereas texture data was collected using a Circular Track Meter and a Laser Texture Scanner. The surface micro-texture was characterized by different texture parameters calculated in both the spectral and the spatial domain. The impact of incorporating the micro-texture on the prediction of skid resistance was evaluated by analyzing a series of models specified by each of the proposed parameters. The results of the analyses show a significant improvement in predicting the surface friction when accounting for both components of the surface texture, as opposed to only the macro-texture. Furthermore, the parameters calculated on the frequency domain led to a better prediction power.

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THE CONTRIBUTION OF MICRO- AND MACRO-TEXTURE TO THE SKID RESISTANCE OF FLEXIBLE PAVEMENT

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Effect of Aggregate Micro- and Macro-texture on Pavement Skid Resistance

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EXECUTIVE SUMMARY

Skid resistance is an important characteristic of the pavement surface to reduce the number of road accidents. The mechanisms involved in the activation of the frictional force required for a safe braking of the vehicle depend on both the macro-texture (wavelengths between 50mm to 0.5mm) and the micro-texture (wavelengths less than 0.5mm) of the pavement surface. The state-of-the-practice methodologies commonly used for measuring pavement texture at highway speeds only account for the macro-texture, which alone might not be sufficient to effectively characterize skid resistance. However, as technology advances and sensors with higher sampling rate and resolution become available, it will be possible to capture both the macro- and the micro-texture of the pavement. This study explored different ways to characterize the micro-texture of pavement surfaces with the main objective of quantifying the effect of accounting for both the micro and the macro components of the texture, rather than just the macro-texture, on the prediction of skid resistance. The different methods to characterize the micro-texture were compared in order to determine which one better predicts pavement friction.

The friction and texture data analyzed in this study were collected from an experiment which included a total of 28 different flexible pavement surfaces. The tested pavement surfaces covered a wide range of friction values, and a number of cases for each possible combination of fine and coarse macro-texture and smooth and sharp micro-texture. The data collection consisted of field measurement of friction and texture performed on the same spot at each the test surfaces. The skid resistance was evaluated under wet condition of the surface using a British Pendulum Tester. The macro-texture was characterized using a Circular Track Meter, while the micro-texture was characterized by a series of different parameters calculated using the surface coordinates scanned by a Laser Texture Scanner.

The scanned test surfaces using the Laser Texture Scanner were transformed to the frequency domain using Fourier Transform and then filtered using an ideal low-pass filter in order to decompose the spatial coordinates into two profiles, each containing the wavelengths of the macro and micro component of the texture respectively. A number of different parameters to characterize the roughness of the profiles were then computed from the scanned surfaces in both the spatial and in the frequency domain. Examples of the computed parameters are the Mean Profile Depth, commonly used by pavement engineers, and the coefficients of the linearized Power Spectral Density. Since there is currently no standard or specification to process and

analyze micro-texture profiles, the study evaluated different configurations, such as different lengths of the segment of analysis, and provides recommendations.

The polishing effect of traffic on the aggregates of the pavement surface might result in lower micro-texture on the higher points of the surface for some types of aggregates. Since all of the surfaces tested for this study consist of in-service pavement surfaces, additional analyses were performed to determine both whether the values of the micro-texture parameters at the peaks of the profiles differed from the ones at the valleys, and how to better characterize the micro-texture in order to improve the prediction of the skid resistance if that occurs. Since only the micro-texture of the contact area between the vehicle tire and the pavement surface affects the development of the frictional forces attributed to the micro-texture asperities, an additional set of micro-texture parameters was evaluated considering only the estimated portion of the surface in contact with the tire patch.

The authors concluded that accounting for both the macro- and the micro-texture components of the surface will significantly enhance the prediction of skid resistance of flexible pavements as oppose to accounting solely for the macro-texture component. Furthermore, the performed analyses showed that the parameters calculated on the frequency domain led to a better prediction power than the parameters calculated in the spatial domain. Such improvement will allow transportation agencies to better manage skid resistance and therefore to improve road safety. Regarding the characterization of the surface micro-texture, the authors strongly recommend accounting for the actual contact area between tire and pavement. In addition, it is recommended to determine the value of the surface micro-texture parameter as the median of the individual segments of analysis using a 1 mm baseline, in order to mitigate the effect of outliers in the texture measurements.

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DISCLAIMER

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Chapter 1. Introduction

There is currently a high demand for safer roads and a need for more effective methods to monitor pavement safety parameters at a network level. Several studies show an increase in the number of crashes as the skid resistance of the pavement decreases (Hall et al., 2009). Monitoring and managing the skid resistance of the highway network is therefore important in order to control and reduce the number of road accidents.

Adequate pavement surface friction is required to provide a satisfactory skid resistance needed to perform a safe braking maneuver. It is well known that the friction coefficient of a surface is affected by texture, among other factors; the rougher the texture, the higher the friction of the surface (Masad et al., 2009). Texture measurements of the pavement surface might then be used to evaluate and monitor skid resistance.

A pavement surface is usually divided into four categories for analysis: unevenness (wavelengths greater than 500 mm), mega-texture (wavelengths between 500 and 50 mm), macro-texture (wavelengths between 50 to 0.5 mm), and micro-texture (wavelengths less than 0.5 mm). The two components of the surface texture that affect skid resistance of the pavement are the macro-texture and the micro-texture (PIARC, 1987). The scale of the macro-texture component focuses on the contact area between the vehicle tire and the pavement surface, while the scale of the micro-texture range of wavelengths focuses on the asperities of the pavement aggregates.

The state-of-the-practice methodologies commonly used for measuring pavement texture at highway speeds only account for the macro-texture, which alone might not be sufficient to effectively characterize skid resistance. However, as technology advances and sensors with higher sampling rate and resolution become available, it will be possible to capture both the macro- and the micro-texture of the pavement. The incorporation of the micro-texture is expected to enhance the prediction of the skid resistance, making it possible to monitor the skid resistance of the highway network using a high-speed non-contact method.

This study uses spot measurements of friction and texture collected at in-service pavements with the objective of quantifying the improvement on the prediction of skid resistance when accounting for both the macro- and the micro-texture of the surface as opposed to only considering the macro-texture component. The study also explores and compares different ways to characterize the surface micro-texture in order to determine which one better predicts surface friction.

The next chapter of this report contains the background and a literature review of the relationship between pavement surface friction and texture, methodologies to measure friction and texture, and a description of current methods to process the measured pavement surface in order to characterize both the micro- and macro-texture components. Chapters 3 describes the data collection procedures used in this study and provides the main characteristics of the measured pavement surfaces.

Chapters 4 and 5 present the processing and analyses of the field measurements of surface friction and texture in order to evaluate the improvement on the prediction of skid resistance when accounting for both the macro- and the micro-texture of the surface as opposed to only considering the macro-texture component. The different methods to characterize the micro-texture were compared in order to determine which one better predicts pavement friction. The last chapter of this report provides the main findings from the assessment of the separate contribution of micro-and macro-texture to the skid resistance of flexible pavement, and recommendations for the calculation of micro-texture parameters.

Chapter 2. Background

This Chapter provides the main concepts and a literature review for establishing the separate contribution of micro- and macro-texture on the skid resistance of flexible pavements.

2.1 Components of Frictional Force

The frictional forces activated on the pavement surface during the skidding of a vehicle are divided into two major components: hysteresis and adhesion forces (Figure 2.1) (Moore and Geyer, 1974; Choubane et al., 2004). Although other mechanisms can be used to explain the loss in kinetic energy of the vehicle, such as abrasion or shear of the tire material, their contribution is negligible compared to the hysteresis and the adhesion mechanisms (Hall et al., 2009). The hysteresis mechanism considers the energy dissipated due to the deformation of the tire material when in contact with the pavement surface. The adhesion mechanism considers the bond atomic forces between the tire and the pavement materials occurring at the micro asperities of the surface (Moore and Geyer, 1974; Persson, 1998).

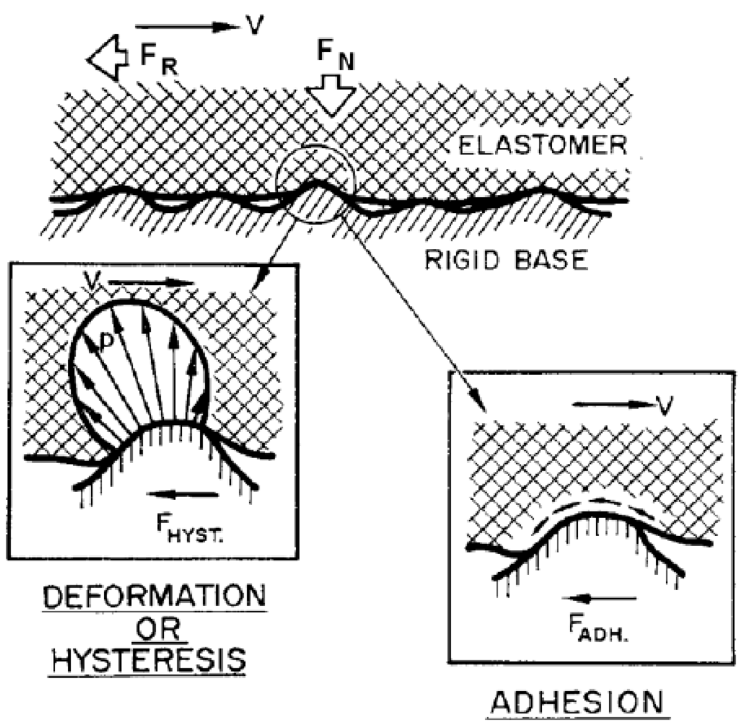

Figure 2.1: Main components of frictional forces between pavement and vehicle (Moore, 1972)

2.2 Relationship between Pavement Texture and Surface Friction

The skid resistance of pavements is affected by both the macro- and the micro-texture components of its surface. Each of the texture components plays a different role in skid resistance. On the one hand, the macro-texture provides the channels for the rapid drainage of water on the surface, reducing the chances of hydroplaning. Also, the rougher the surface macro-texture, the more the tire material is deformed, and therefore the greater the magnitude of the hysteresis component of the frictional force. On the other hand, the sharper the micro-texture asperities, the greater the surface area between the tire and the pavement, and therefore the greater the magnitude of the adhesion component of the frictional force. For the case of wet pavements, the micro-texture contributes to skid resistance by breaking the thin layer of water on the surface, promoting contact between pavement and tire necessary for developing the inter-atomic attractive forces of the adhesion component (Masad et al. 2009; Noyce et al. 2005; Do et al., 2000).

The adhesion component of the frictional force relates to the actual contact area between the vehicle tire and the pavement surface (Choubane et al., 2004). Therefore, a micro-texture parameter designed with the objective of explaining skid resistance of the pavement should account for the portion of the pavement in contact with the vehicle tire.

2.3 Measuring Skid Resistance of Pavements

Some of the commonly used methods for the evaluation of the skid resistance of pavements are the British Pendulum Tester (BPT), the Dynamic Friction Tester (DFT, see Figure 2.2) and the Locked-Wheel Skid Trailer. The BPT and the DFT provide a spot measurement of the surface friction and they can be used either in the laboratory or in the field. The former measures the friction coefficient at a skidding speed of approximately 10 km/hr (Henry, 2000), and therefore evaluates the skid resistance at lower speeds. The latter allows for measuring the friction of the surface as a function of speed, for a range of different speeds.

Figure 2.2: Dynamic Friction Tester

The Locked-Wheel Skid Trailer instead evaluates the high-speed skid resistance (usually performed at 64 km/hr) of the pavement wet surface, using a locked wheel with typically a ribbed or smooth tire skidding along a stretch of pavement. This test is usually used to conduct network surveys. However, the portion of the highway network surveyed is limited by the practical limitation of having to refill the Locked-Wheel Skid Trailer water tank after a number of tests.

2.4 Measuring Texture of Pavement Surfaces

Traditional methods to measure the surface texture of a pavement are the Sand Patch, the Grease Patch or the Outflow Meter. These methods provide an indirect measurement of the surface depth at a discrete spot on the pavement and are not sensitive to the micro-texture asperities. Detailed information about these methods can be found in the NCHRP Synthesis 291 (Henry, 2000). More modern methods instead scan the surface coordinates using a laser sensor and calculate parameters to characterize the texture of the pavement, e.g. the Mean Profile Depth (MPD). Some of these methods provide a spot measurement of the pavement, such as the Circular Track Meter (CTM), while others are capable of measuring the texture continuously along the road at highway speeds, such as the INO Laser Cracking Measuring System (LCMS) or the Texas Department of Transportation's (TxDOT) 3D Texture Scanner (TTS).

Therefore, although current technologies allow for measuring the pavement texture of the road continuously at highway speed, none of them are capable of capturing the micro-texture component of the surface.

The following two sections describe two different devices used to quantify pavement micro-texture statically: Aggregate Imaging Measurement System (AIMS) and Laser Texture Scanner (LTS).

2.4.1 Aggregate Imaging Measurement System (AIMS)

Pavement surface texture is influenced by many factors, such as aggregate type and size, mixture gradation, and texture orientation among others. The AIMS (Figure 2.3) is designed to analyze, using camera, lighting, and microscope technology, the particle geometry of coarse and fine aggregates through three independent properties: form, angularity (or roundness), and surface texture. Coarse aggregates sizes passing the 37.5 mm sieve and retained on the 4.75 mm (No. 4) sieve can be evaluated, as well as fine aggregate passing the 4.75 mm (No. 4) sieve and retained on the 0.075 mm (No. 200) sieve.

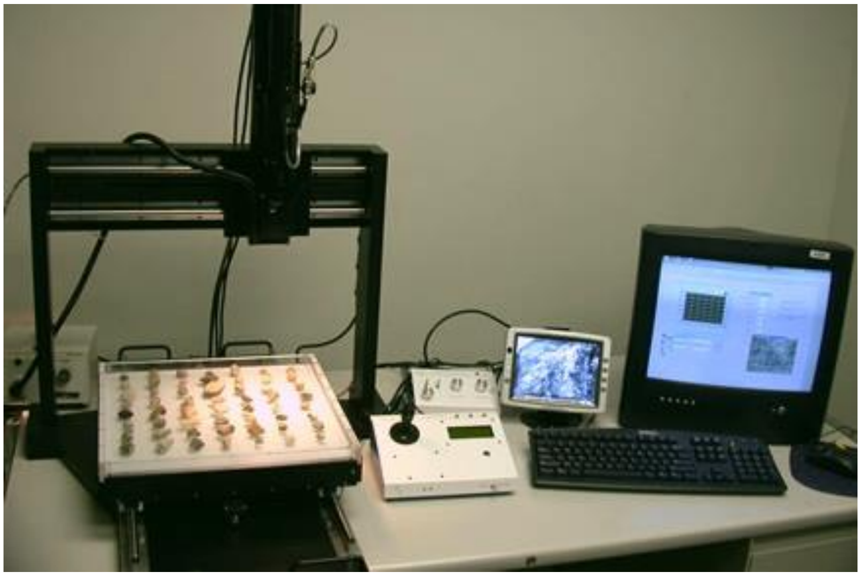

Figure 2.3: AIMS device (Mahmoud et al., 2010)

The classification methodology can be used for evaluating the effect of different processes, such as crushing techniques and blending, on aggregate shape distribution, and for the development of aggregate specifications based on the distribution of shape characteristics (Masad et al., 2005). It also has the capability to characterize the surface of asphalt cores for micro- and macro- texture parameters.

In order to perform this analysis, the device captures images at different resolutions with a camera, and uses different arrangements of lightning (bottom and top lightning) to provide uniform illumination. In this way, different image analysis techniques can provide accurate results.

AIMS uses a three dimensional analysis of coarse particles, which allows distinguishing between flat, elongated, or flat and elongated particles. On the other hand, a two dimensional analysis is used for fine particles. In addition, by using the fundamental gradient and wavelet methods, it quantifies angularity and the surface texture respectively (Masad et al., 2005). Pavement micro-texture can be described by the surface texture of the aggregates.

If the particles analyzed are coarse, black and white images are used to quantify form and angularity (Figure 2.4), while gray images are used for texture (Figure 2.5). These aggregates are analyzed individually by placing them in a backlighting sample tray which has marked grid. On the other hand, black and white images are used to evaluate all these properties in fine particles. In this case, the particles are randomly placed on the aggregate tray with the backlight turned on.

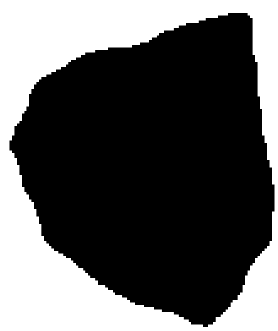

Figure 2.4: Coarse Aggregate Image

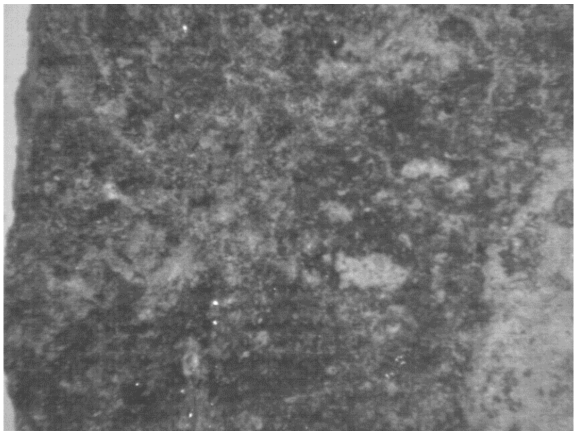

Figure 2.5: Coarse Aggregate Texture

The AIMS angularity chart provides objective characterization of the material edge characteristics. AIMS angularity characterizes the particle edge sharpness characteristics on a scale of 0-10000.

To describe the texture content at a given resolution or decomposition level, a parameter called the wavelet texture index is defined. The texture index at any given decomposition level is the arithmetic mean of the squared values of the detail coefficients at that level. The texture information lies in the detail coefficients LH, HL, and HH (Figure 2.6). The LH coefficients pick up the high frequency content in the vertical direction, the HL coefficients pick up the high frequency content in the horizontal direction, and the HH coefficients pick up the high frequency content in the diagonal direction (Masad et al., 2005).

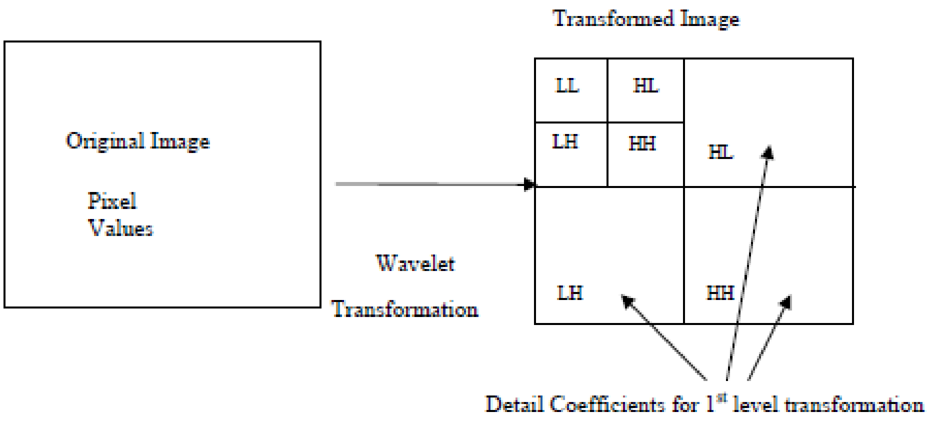

Figure 2.6: Two-level Wavelet Transformation (Masad et al., 2005)

2.4.2 Laser Texture Scanner (LTS)

The LTS (Figure 2.7) is a lightweight and portable equipment produced by Ames Engineering, designed to scan the pavement surface coordinates in order to characterize its texture content. The resolution of the LTS allows to measure and describe the two decades of the macro-texture (wavelengths from 50 mm to 5 mm and from 5 mm to 0.5mm) and the first decade of the micro-texture (wavelengths from 0.5 mm to 0.05 mm). This device uses a laser sensor to scan the surface coordinates of parallel straight lines with a sampling rate of one point every approximately 0.015 mm. It has a maximum scan length of 4.1 in (104.14 mm), and a maximum scan width of 3.0 in (76.20 mm), which allows a maximum of 1200 line scans (spacing of 0.064 mm between lines). The scanner will perform the selected amount of lines scans of equal spacing over the width. The LTS is placed on the surface through three point contact legs.

Figure 2.7: Laser Texture Scanner (AMES, 2010)

The LTS has the ability to control the intensity of the laser spot. Half power setting works best when scanning bright white surfaces with no sunlight striking the surface of the scan area. Direct sunlight will cause spikes to occur in the data and will elevate the measurements being made. On the other hand, the full power setting works best for very dark surfaces, or for scanning outside in the sunlight. If full power is used on very white surfaces, small spikes may occur in the scan data. Spikes occur when the laser cannot see the bottom of a deep crack because of the angle of the returning light to the detector. The sensor increases the intensity of the laser light causing the crack in the scanned surface to glow, which confuses the detector and creates a spike in the data (AMES, 2010). In addition, the LTS is equipped with rechargeable batteries and a GPS receiver which allows to track the location of each texture measurement taken in the field.

2.5 Processing of Scanned Pavement Surfaces

This section discusses the motivation, and limitations of the two different methods for characterizing the micro-texture contained in the Laser Texture Scanner (LTS) pavement surface profiles. The pavement surface scans produced by the LTS system consist of parallel line scans of the profile elevation as a function of the longitudinal distance along the pavement surface. This provides a profile elevation of the entire surface. The transforms used in this study are all compatible with one dimensional signals, so the individual line scans of the pavement surface were analyzed independently.

2.5.1 Fourier Transform

The FT transforms a signal into a sum of sinusoidal waves, which is accomplished by projecting the signal onto sinusoidal waves of different frequency content. Sine and cosine waves of frequency content differing by an integer multiple are orthogonal functions, so the FT uses an infinite number of these waves as basis functions that span all of function space. Thus, the output of the FT consists of the amplitudes corresponding to each frequency. This information can be displayed in Power Spectral Density (PSD) plot, in which the square of the amplitude is plotted against its corresponding frequency.

Due to the discrete nature of the scans produced by the LTS, the Discrete Fourier Transform (DFT) is used in this study. An important property of the DFT is that it obeys the Nyquist Sampling Theorem, which states that the sampling frequency should be at least twice the highest frequency contained in the original signal. An alternate way to interpret this statement is that the smallest wavelength that can be obtained from a discrete signal is twice the sample spacing. The smallest wavelength in the first decade of micro-texture wavelengths (i.e. 0.05 mm) is greater than two scanned points, and therefore, the FT captures all the information in this frequency range.

Another important property of the FT is that its basis functions are continuous functions and, therefore, an infinite number of continuous functions would be required to accurately describe sharp edges and other discontinuities potentially present in a scanned pavement surface. Figure 2.8 illustrates this limitation, in which the FT of a sinusoidal wave of one frequency with discontinuities produces relatively large amplitudes for frequencies not contained in the original signal. These frequencies are called harmonics, and occur because of the discontinuities caused by the absolute value operation. The power of these harmonics extend into the micro-texture region of the PSD, which could potentially hide or confound the information contained in the actual signal.

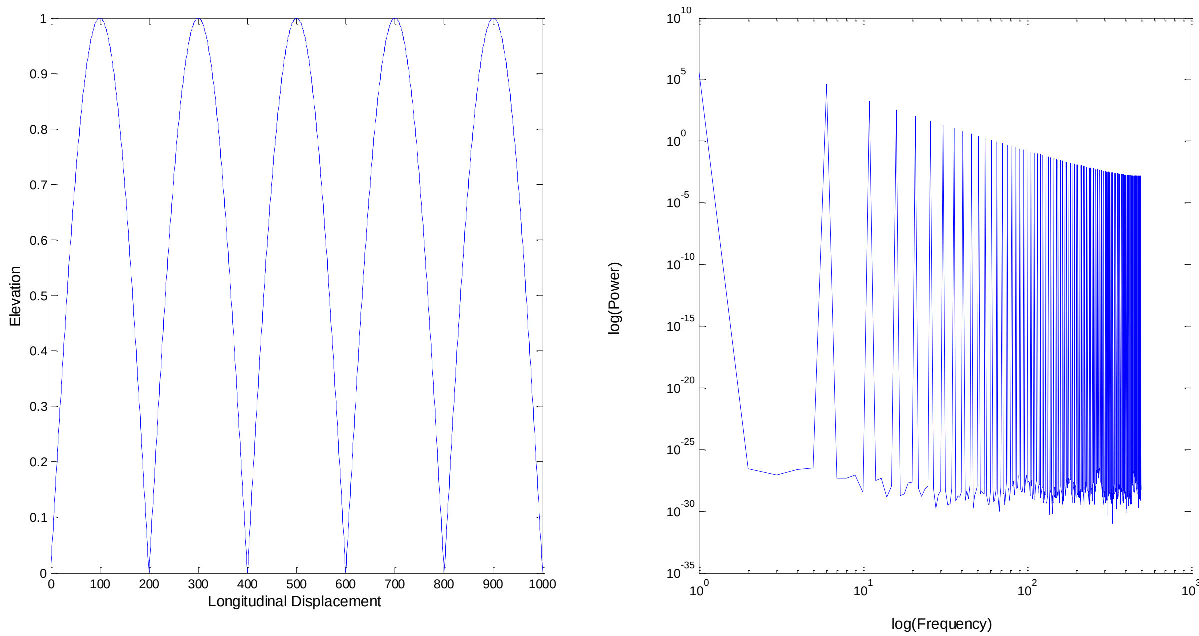

Figure 2.8: (a) Plot of a abs(sin(2πx/400)) on the left; (b) PSD of this signal on the right

Another limitation of the FT approach is given by the non-stationary nature of small selections of a surface scan. A stationary signal is a signal such that the elevation probability distribution of an analyzed window of the signal does not change as the window is translated longitudinally. FT assumes that the signal is stationary which might not be the case for short segment of pavement surface profiles and therefore the FT approach does not always produce ideal results.

Chapter 3. Texture and friction data collection

The data used in the current study consisted of spot measurements of surface texture and friction performed on twenty-eight different in-service flexible pavements located in Texas near Austin, Yoakum, and San Antonio. Twenty-four of these test surfaces were used for a different research project, in which the objective was to evaluate equipment for the light texturing of pavement surfaces. This set of data included the measurement of texture and friction before and after applying the texturing treatment (twelve sections for each case). The remaining surfaces were specially selected in order to obtain a final dataset that covers a wide range of friction coefficient values and includes different cases for each possible combination of fine and coarse macro-texture and smooth and rough micro-texture (Table 3.1). Figure 3.1 shows examples of pavement surfaces for each of the combination of micro- and macro-texture levels.

This section describes the methodologies used to evaluate the skid resistance of the pavement, documents the equipment and methodologies used to characterize the surface texture and presents the summary statistics of the collected data for the twenty-eight pavement surfaces.

Table 3.1: Combination of fine and coarse macro-texture and smooth and rough micro-texture

Types of Pavement surface texture		MACRO-TEXTURE	
		FINE	*COARSE*
MICRO-TEXTURE	*SMOOTH*		
	SHARP		

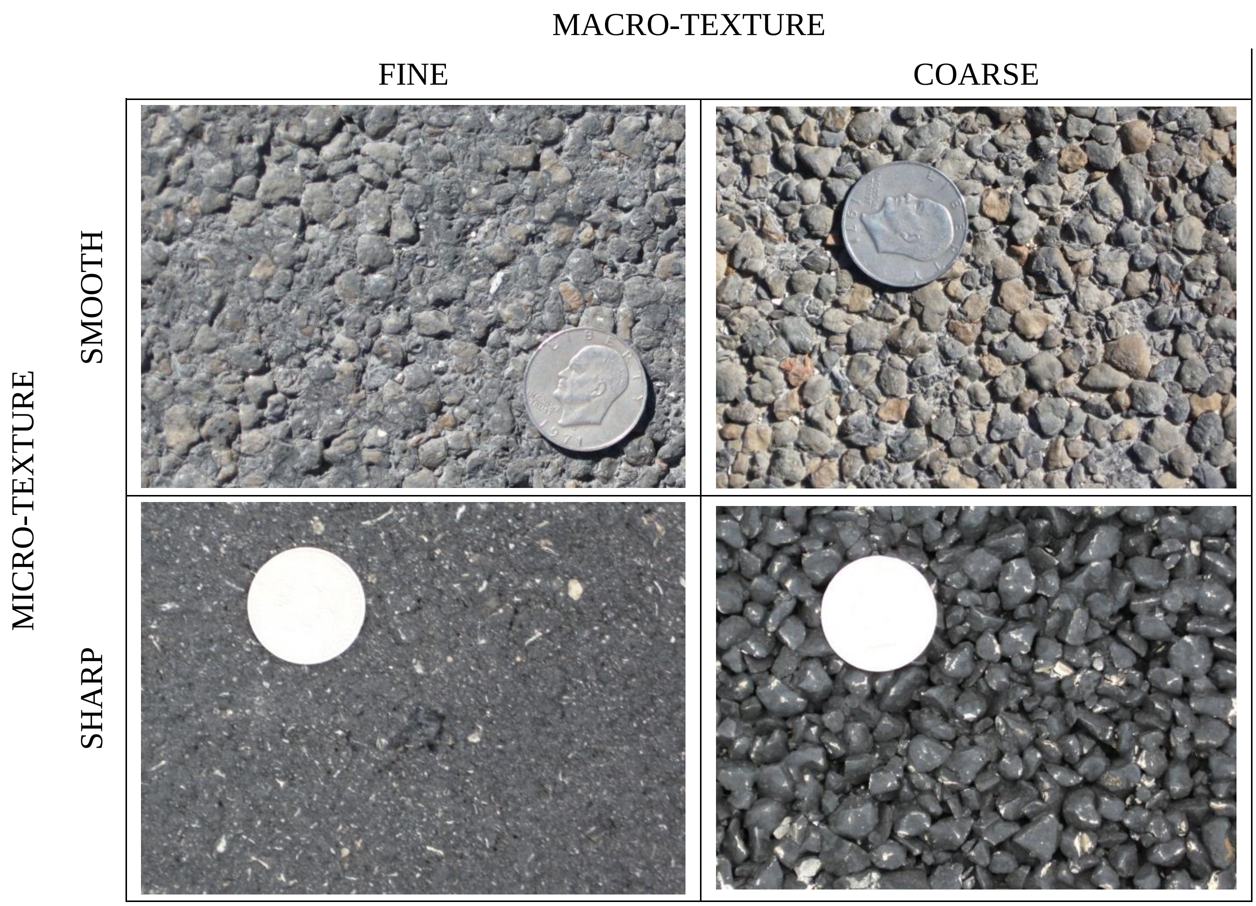

Figure 3.1: Pavement surfaces for each of the combination of micro- and macro-texture levels

3.2 Friction Measurements

The skid resistance of the pavement surfaces was evaluated using the British Pendulum Tester shown in Figure 3.2. The device was calibrated just before performing the tests and a new rubber pad was conditioned using sand paper as indicated in the annex of the ASTM E303-98 specification.

Each test was performed following the procedure indicated in ASTM E303-98 for the case of field measurements and wet condition of the pavement surface. The British Pendulum Number (BPN) of the test surface was computed as the mean value of the individual BPN of five consecutive swings. All test surfaces were tested in the direction of traffic.

Figure 3.2: British Pendulum Tester

An additional number of friction tests were carried out on four of the test surfaces to estimate the testing error specific to the conditions of our data collection. Nine friction tests were performed on each of the four test surfaces for both the wet and dry condition of the pavement. The testing error of each of the tests was computed as indicated in the ASTM E303 specification; i.e., the standard deviation of the BPNs from the five swings divided by the square root of the number of swings, and multiplied by 1.96 to obtain the upper limit of the 95% confidence interval of the error. The mean testing error of the 36 (= 9 tests/surface * 4 surfaces) friction tests was 0.93 for the dry condition and 0.65 for the wet condition. Therefore, the testing error fell within 1.00 BPN at a 95 % confidence level.

3.3 Texture Measurements

The texture data collection consisted of scanning the surface coordinates in order to calculate the parameters to characterize the macro and micro components of the texture separately. The coordinates of each test surface were scanned using a Circular Texture Meter (CTM) and a Laser Texture Scanner (LTS). The CTM is widely used by researchers and transportation agencies to measure texture whereas the LTS has been recently developed by AMES Engineering.

3.3.1 Macro-Texture Measurements.

Figure 3.3 shows the CTM used in the experiment. The CTM is a laser scanner that scans a 892 mm long circumference of the pavement with a sampling rate of 1 point every 0.87 mm. The scanned circumference is further divided into eight 100 mm long segments for analysis. Therefore, the CTM describes the wavelengths between 1.7 mm and 100.0 mm for each of the segments and, as such, is used to characterize the macro-texture of the pavement.

Figure 3.4 shows a screenshot of the software used to operate the CTM and calculate the Mean Profile Depth (MPD) for each of the eight segments of the scanned circumference. These MPD values were calculated according to ASTM E1845-09, and averaged to obtain the MPD of the test surface. The macro-texture MPD used in the analyses consisted of the average value of three test replicates. Figure 3.4 shows the scanned coordinates of the circumference for the three replicates of one of the tests.

Figure 3.3: Circular Texture Meter

Figure 3.4: Screenshot of CTR output with scanned coordinates on the right

3.3.2 Micro-Texture Measurements.

Figure 3.5 shows the Laser Texture Scanner (LTS) used to collect micro-texture data for the study. The LTS uses a laser to scan the coordinates of parallel straight lines with a sampling rate of 1 point every approximately 0.015 mm. The length of each scanned line can be set to a maximum of 4.1 inches (104.1 mm), resulting in a maximum of 7212 points per profile. The number of parallel scanned lines can be set to a maximum of 800 lines within a distance of 3 inches (76.2mm), resulting in a minimum distance between parallel lines of 0.09 mm.

The time required for the LTS used in the experiment to scan eight hundred 100 mm long lines is greater than 2 hours. Due to time constrains and since the LTS data was used only to characterize micro-texture, the number of lines was set to 400 lines within 2 inches (50.8 mm) and the length of the lines was set to 2 inches (50.8 mm). Therefore, the LTS was set to scan a 50.8 mm long and 50.8 mm wide area of the pavement. Figure 3.6 shows the scanned 3D coordinates of one of the tests surfaces. All test surfaces were scanned in the direction of traffic.

The high sampling rate of the LTS makes it possible to describe the wavelengths of the surface between 0.03 mm to 50 mm, and therefore it can be used to characterize the first decade of the micro-texture (wavelengths between 0.05 mm to 0.50 mm). The coordinates of the 400 scanned lines were used to calculate a series of parameters to characterize micro-texture. The definitions and calculations of these parameters are described in the next section of the paper.

Figure 3.5: Laser Texture Scanner used in the study

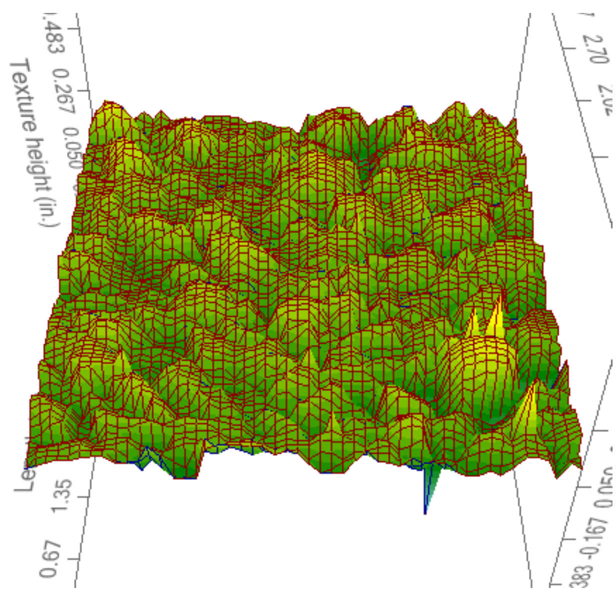

Figure 3.6: 3D coordinates of scanned surface using the LTS

3.3.3 Summary Statistics of Collected Data

Table 1 presents the friction and texture characteristics of the 28 tests surfaces collected for the study. All test sections consisted of dense-graded hot-mix asphalt pavements. The second column of the table indicates whether the pavement surface has been treated or not; the third column reports the friction values measured using a BPT; and the fourth and fifth columns present the MPD values of the surface macro- and micro-texture.

Table 3.2: Texture and Friction Characteristics of the Evaluated Pavement Surfaces

Test Section	Texture Treatment	Friction	Texture (MPD)		Test Section	Texture Treatment	Friction	Texture (MPD)	
			Macro	Micro				Macro	Micro
		BPT	CTM	LTS			BPT	CTM	LTS
#	-	*BPN*	*mm*	*mm*	*#*	-	*BPN*	*mm*	*mm*
1	unmilled	78	2.60	0.732	*15*	unmilled	65	0.73	0.157
2	unmilled	74	2.95	0.474	*16*	unmilled	80	1.02	0.694
3	unmilled	70	0.67	0.180	*17*	milled	105	2.97	0.777
4	unmilled	70	0.94	0.194	*18*	milled	85	3.13	0.950
5	unmilled	65	0.89	0.322	*19*	milled	93	3.41	0.627
6	unmilled	55	1.12	0.284	*20*	milled	65	1.01	0.139
7	unmilled	60	1.01	0.198	*21*	milled	68	1.05	0.207
8	unmilled	56	0.93	0.153	*22*	milled	88	1.81	0.443
9	unmilled	55	0.88	0.130	*23*	milled	68	2.13	0.193
10	unmilled	55	1.12	0.161	*24*	milled	85	3.11	0.581
11	unmilled	55	0.86	0.169	*25*	milled	90	2.08	0.232
12	unmilled	58	0.98	0.167	*26*	milled	73	1.62	0.493
13	unmilled	58	1.00	0.166	*27*	milled	71	1.95	0.185
14	unmilled	60	1.13	0.175	*28*	milled	80	1.83	0.315
Parameter				Units	# Obs	Mean	Std Dev	Min	Max
Friction – BPN				BPN	28	71	13.4	55	105
Macro-texture – MPD				mm	28	1.60	0.86	0.67	3.41
Micro-texture – MPD				mm	28	0.028	0.005	0.021	0.041

The measurements of friction, and texture were all performed in the same spot at each of the 28 test surfaces. Texture data was always collected prior to friction to ensure the dry condition during the scanning of the surface. The surface coordinates scanned by the CTM were used to calculate the MPD of the macro-texture. The surface coordinates scanned using the LTS were used to calculate different parameters to characterize the micro-texture, such as the MPD and the Root Mean Squared (RMS).

Table 1 presents the summary statistics of the friction and texture data collected for the study. Among the several calculated micro-texture parameters, the one used to describe the tests surfaces of the study is the MPD with a 1 mm baseline.

Table 3.3: Summary Statistics of Collected Texture and Friction Data

Parameter	Units	Obs	Mean	Std Dev	Min	Max
Skid Resistance – BPN	-	28	71	13.4	55	105
Macro-texture - MPD_{macro}	mm	28	1.60	0.86	0.67	3.41
Micro-texture - MPD_{micro}	mm	28	0.028	0.005	0.021	0.041

Chapter 4. Characterization and Processing of Micro-Texture Data

The scanned test surfaces using the LTS were decomposed into two profiles, each containing the wavelengths of the macro and micro component of the texture respectively. The calculated parameters and analyses performed to characterize the micro-texture of each test surface were applied to the filtered profiles. This section describes the processing applied to the scanned surfaces and presents the calculated parameters.

4.1 Processing of Texture Data

The spatial coordinates scanned by the LTS were processed in order to filter the micro-texture component of the surface texture. The scanned lines were transformed to the frequency domain using Fourier Transform and then filtered using an ideal low-pass filter. The profiles in the frequency domain were cut off between the wavelengths 0.05 mm to 0.50 mm to obtain the micro-texture profile and between 0.50 mm and 50.0 mm to obtain the macro-texture profile.

4.1.1 Spectral Analysis.

The Power Spectral Density (PSD) was calculated for each of the test surfaces in order to analyze the relative impact of a group of frequencies on the surface friction as measured by the BPT. The PSD of each test surface was estimated as the mean of the individual PSDs for the 400 scanned lines per surface, as proposed by Elson et al., (1995). Figure 4.1 presents the PSD of four test surfaces as a function of frequency (and wavelength) in a double logarithmic scale. This graph includes the frequencies corresponding to the first decade of the macro- and micro-texture respectively.

A linear relationship between the log of the PSD and the log of the frequency is noted in Figure 4.1. The correlation coefficient between the set of log(PSD) and log(frequency) was observed to be greater than 0.98 for the 28 test surfaces, indicating a strong linear relationship between them for all surfaces. This implies that the micro-texture of the test surfaces can be characterized in the frequency domain using two parameters: the slope and “y” intercept of a straight line fitting the observed log(PSD) and log(Frequency).

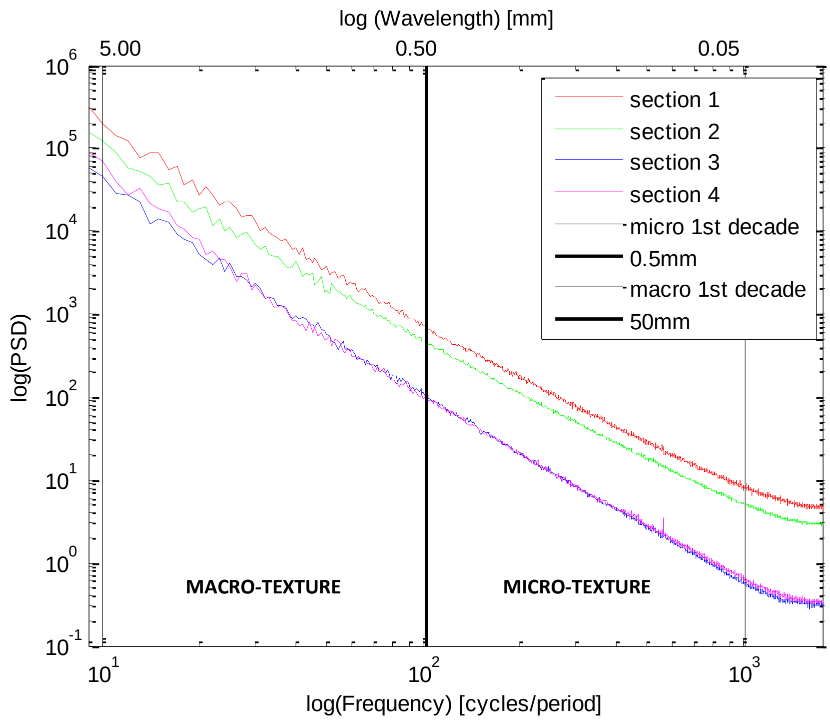

Figure 4.1: Power Spectral Densities of four scanned surfaces

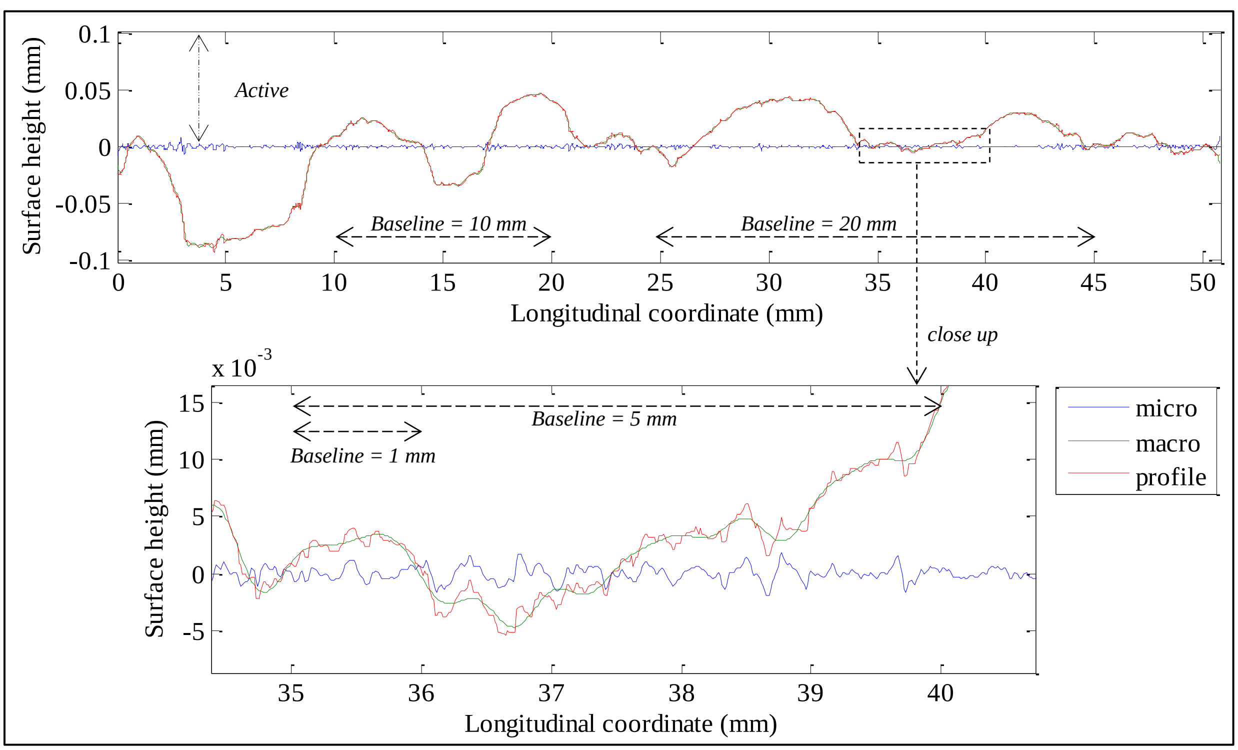

Figure 4.2: (a) Line scan of pavement surface with filtered micro- and macro-texture components (above) and (b) close up of line scan profile (below)

4.1.2 Processing in Spatial Domain.

The filtered profiles were then transformed back to the spatial domain, obtaining the coordinates of profiles formed only by the wavelengths of the first decade of the micro-texture. Since the ringing artifacts due to having applied an ideal low-pass filter were more evident in the extremes of the lines, the micro-texture profiles of each test surface were truncated by not considering the first and last 5 mm of each profile. Therefore, the micro-texture profiles used for the calculation of parameters in the spatial domain were 40 mm long each.

Figure 4.2 shows the coordinates of a scanned line (in red) along with the filtered macro-texture (in green) and micro-texture profiles (in blue). The graph at the top (Figure 4.2-a) shows the coordinates for the entire 50.8 mm whereas the graph at the bottom (Figure 4.2-b) shows a close-up of the scanned line between the longitudinal coordinates of 35 mm and 40 mm. The macro-texture profile is formed by subtracting the higher frequencies, which provide the fine details of the curve (asperities of the surface), from the original profile. Therefore, the macro-texture is a smoothed version of the scanned profile, as it can be noted from the close-up figure (Figure 4.2-b).

The next step in the processing of the scanned surfaces consisted of dividing the micro-texture profiles into shorter segments for their characterization. While the standard to calculate the MPD of macro-texture profiles (ASTM E1845-09) specifies to analyze the surface profile in segments 100 mm long, there is currently no specified baseline for the analysis of the micro-texture profile. Each micro-texture parameter was calculated using four different baselines: 1 mm, 5 mm, 10 mm and 20 mm. These four baselines are illustrated in Figure 4.2. Since the sampling rate of the LTS was 70 coordinates per millimeters, the shortest baseline (1 mm) comprises 70 points and the longest one (20 mm) comprises 1,400 points.

4.2 Calculation of Micro-Texture Parameters

Once the micro-texture profiles of each test surface were segmented adopting the different baselines, a series of parameters to characterize the roughness of the profiles were calculated. These parameters can be categorized into spectral and spatial parameters depending on whether they were calculated in the frequency or in the spatial domain. The spectral parameters consisted of the intercept and slope of the PSD as a function of the frequency on a log-log scale. The spatial parameters can be further divided into the amplitude and the slope parameters depending on whether they were calculated using the amplitude or the slopes of the profiles.

4.2.1 Spectral Parameters

The intercept and slope of the linearized PSD were obtained by estimating the parameters of a linear model predicting the logarithm of the PSD as a function of the logarithm of the frequency for each surface. The parameters of the models were estimated using Ordinary Least Square (OLS) regression.

4.2.2 Amplitude Parameters.

The amplitude parameters use the height values of the filtered profiles to characterize the micro-texture. The formulae of each of the calculated amplitude parameters are the following:

- Mean Profile Depth: $MPD = \frac{1}{2}\left[\max\left(h_1, .., h_{N/2}\right) + \max\left(h_{N/2+1}, .., h_N\right)\right]$ (1)
- Root Mean Squared: $RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} h_i^2}$ (2)
- Maximum Height of the Profile: $MPH = \max(h_i) - \min(h_i)\,,\;\; i = 1..N$ (3)

Where h_i is the height value for coordinate "i", and N is the number of coordinates within the baseline.

4.2.3 Slope Parameters.

The slope (or spacing) parameters use the slope values of the micro-texture profiles. The slopes values were calculated using two different formulae. One measures the slopes between two consecutive points as the difference in height between two consecutive coordinates divided by the horizontal distance between them (Equation 4). The second calculates the slopes using a weighted sum of the height values of six coordinates divided by the horizontal distance between them (Equation 5), as proposed in ASME B46.1 (2009). The slope parameters for each test surface were calculated for each of the four analyzed baselines.

The formulae of each of the slope parameters calculated for the study are the following:

- Two-Points Slope Variance: $SV_{2pts} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{h_{i+1}+h_i}{\Delta x}\right)^2}$ (4)

- Six-Points Slope Variance:

$$SV_{6pts} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{h_{i+3}-9*h_{i+2}+45*h_{i+1}-45*h_{i-1}+9*h_{i-2}-h_{i-3}}{60*\Delta x}\right)^2} \quad (5)$$

Where Δx is the horizontal distance between coordinates.

The representative value of each test surface was determined as both the mean and the median of the set of parameters calculated for the individual segments of the micro-texture profiles. Thus, two different sets of results were produced for each baseline and parameter in order to evaluate whether using the median or the mean leads to a better prediction of the surface friction.

4.2.4 Accounting for Contact Area between Vehicle Tire and Pavement Surface.

An additional set of each of the presented micro-texture spatial parameters was calculated for each test surface considering only the portion of the surface in contact with the tire patch (active area).

The active area was estimated as the portion of the surface above the mean height of each of the scanned profiles (Figure 4.3). Since the scanned profiles were normalized with respect to their average height, the active area comprised the coordinates having a positive height value (Figure 4.2-a). Therefore, the micro-texture parameters were calculated using only the subset of segments that have a mean height greater than zero for each of the adopted baselines.

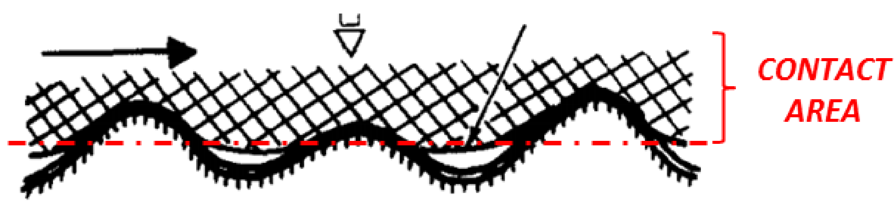

Figure 4.3: Contact area between the tire and the pavement (adapted from Moore, 1980)

Chapter 5. Analyses of Micro-Texture Data

This section presents the analyses conducted on the micro-texture profiles obtained by processing field measurements of pavement surface coordinates. The analyses explore different ways to characterize the micro-texture of pavements and evaluate which ones better predict the skid resistance of the pavement surface.

5.1 Skid Resistance as a Function of Macro-Texture

Figures 5.1 and 5.2 present the relationship between the skid resistance and the macro-texture (on the left) along with the skid resistance and the micro-texture (on the right) for the 28 tested pavement surfaces respectively. From both graphs in Figures 5.1 ad 5.2 it is observed that the skid resistance increased linearly as both the micro- and the macro-texture increased. Therefore, the skid resistance will be explained by means of the texture components of the surface using linear regression models.

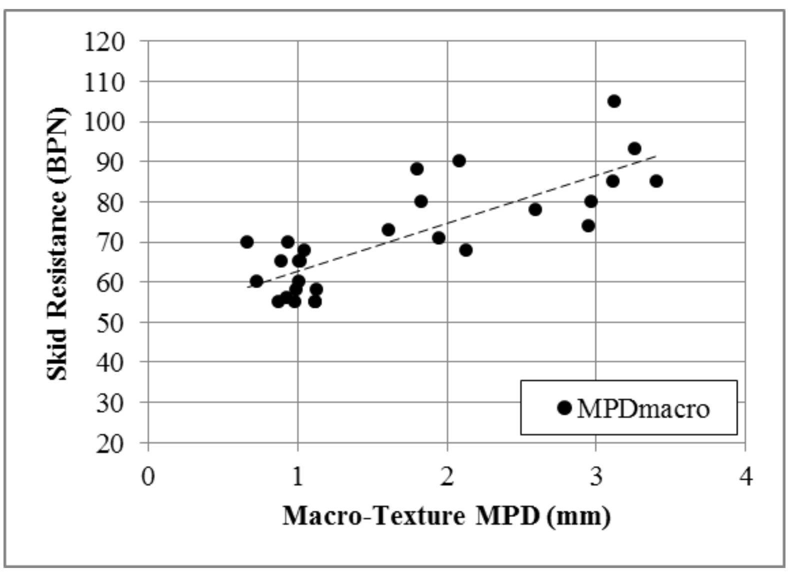

Figure 5.1: Relationship between skid resistance and macro-texture MPD

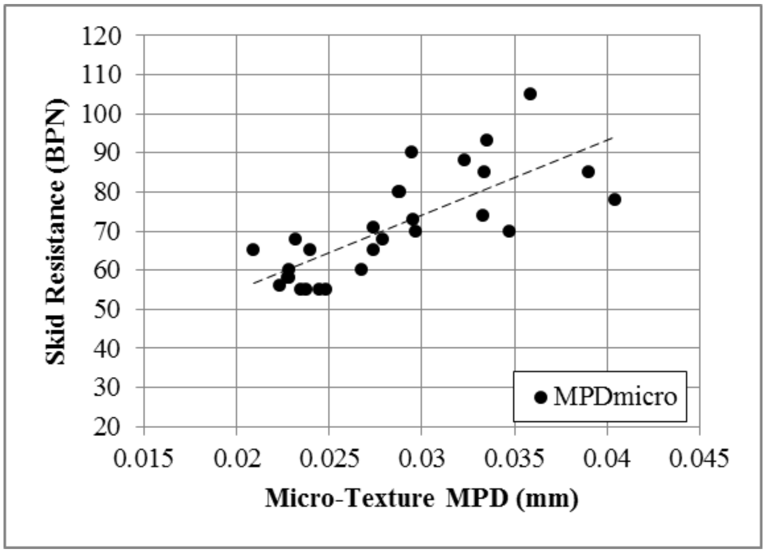

Figure 5.2: Relationship between skid resistance and micro-texture MPD

A linear model between the skid resistance and the macro-texture was estimated and used as the reference when evaluating the impact of incorporating the micro-texture parameters into the prediction. Since the set of tested surfaces comprises some surfaces that have received a light texturing treatment and some others that have not, an indicator variable was included in order to capture the effect of the treatment on the BPN.

The specification of the reference model is the following:

$$BPN = \alpha + \beta_{Macro_{MPD}} * Macro_{MPD} + \beta_{treat} * Treat \qquad (6)$$

Where $Macro_{MPD}$ is the MPD value of the surface macro-texture, and $Treat$ is a dummy variable that takes the values of 1 when the section has received light texturing and 0 otherwise.

The parameters of the linear regression model were estimated using Generalized Least Squares (GLS) estimation, and the results are presented in Table 2. From the table it is observed that both the macro-texture MPD and the treatment indicator were significant in explaining the measured BPN with more than a 90% confidence level. It can also be observed that the BPN increased as the macro-texture MPD increased, as expected, and that the BPN was greater, on average, for the section that received treatment.

Table 5.1: Summary Statistics of Estimated Reference Model

Variable	t-stat	p-value	Adjusted R^2
$\beta_{Macro_{MPD}}$	4.84	0.00	0.670
β_{Treat}	2.61	0.02	

5.2 Effect of Incorporating the Micro-Texture Parameters on Prediction of Skid Resistance

The impact of incorporating the micro-texture on the prediction of skid resistance was studied by analyzing the statistics of a series of linear models specified by adding each of the calculated micro-texture parameters to the reference model (Equation 6). Each of these models was also estimated using GLS.

5.2.1 Spectral Parameters.

The specification of the model including the spectral parameters of the micro-texture was:

$$BPN = \alpha + \beta_{MPD_{macro}} * Macro_{MPD} + \beta_{treat} * Treat + \beta_{lPSD_{intercept}} * lPSD_{intercept} + \beta_{lPSD_{slope}} * lPSD_{slope} \tag{7}$$

Where $lPSD_{intercept}$ and $lPSD_{slope}$ are the intercept and slope respectively of the linearized PSD of the surface micro-texture.

The results of the estimation of the model including the spectral parameters (Equation 7) are presented in Table 3, under the columns of “Model A”. From Table 3 it is observed that the Adjusted R^2 of the Model A increased with respect to the reference model, implying that the incorporation of the micro-texture spectral parameters improved the prediction of the skid resistance of the pavement. It is also observed that the intercept of the linearized PSD significantly affected the BPN whereas the slope didn’t. Therefore, the slope of the linearized PSD of the micro-texture was removed from the previous specification and the results of this new model are presented in Table 3, under the columns of “Model B”. It can be observed from the table that this model presents a higher Adjusted R^2, and that the BPN increased as the value of the intercept of the linearized PSD increased.

Table 5.2: Summary Statistics of the Estimated Models Incorporating the Micro-Texture Spectral Parameters

Variable	Model A			Model B		
	t-stat	p-value	Adjusted R^2	t-stat	p-value	Adjusted R^2
$\beta_{Macro_{MPD}}$	2.22	0.04	0.764	2.63	0.01	0.775
β_{Treat}	4.06	0.00		4.19	0.00	
$\beta_{lPSD_{intercept}}$	2.52	0.02		3.16	0.00	
$\beta_{lPSD_{slope}}$	-0.08	0.94		-	-	

Note: Adjusted R2 before incorporating micro-texture parameters = 0.670

5.2.2 Spatial Parameters

The specification of the models including the spatial parameters of the micro-texture for each of the four adopted baselines was:

$$BPN = \alpha + \beta_{MPD_{macro}} * Macro_{MPD} + \beta_{treat} * Treat + \beta_{treat} * Micro_{param_i}^{baseline_j} \qquad (8)$$

Where $Micro_{param_i}^{baseline_j}$ is the micro-texture spatial parameter "i" computed using the baseline "j".

Since the value for each spatial parameter was determined using both the mean and the median of the set of calculated values for the 400 micro-texture profiles of the scanned surface, two different models were estimated for each baseline in order to evaluate whether using the median or the mean leads to a better prediction of the BPN. The Adjusted R^2 and the t-statistic of the micro-texture parameter for each of the estimated models are presented in Table 4.

As it can be observed from Table 4, both the Adjusted R2 and the t-statistic decrease as the baseline increases in length. Therefore, using a shorter baseline to characterize the micro-texture made each parameter a better predictor of the BPN. Another interesting observation from Table 4 is that the spatial parameters improved the prediction of the BPN when calculated as the median of the values for the individual micro-texture profiles with respect to the mean approach.

This observation holds true for all the analyzed spatial parameters regardless of the baseline used, and it might be due to the fact that the median of the set is less affected by outliers than the mean.

Table 5.3: Adjusted R^2 and t-statistic (in brackets) of the Estimated Models Incorporating the Micro-Texture Spatial Parameters

<table>
<tr><th colspan="7">Adjusted R^2 (t-stat of β_{micro})</th></tr>
<tr><th colspan="3" rowspan="2">Micro-texture Parameter</th><th colspan="4">Baseline</th></tr>
<tr><th>1 mm</th><th>5 mm</th><th>10 mm</th><th>20 mm</th></tr>
<tr><td rowspan="6">Amplitude</td><td rowspan="2">MPD</td><td>Median</td><td><u>0.739 (2.63)</u></td><td><u>0.703 (1.81)</u></td><td>0.669 (0.95)</td><td>0.660 (0.65)</td></tr>
<tr><td>Mean</td><td>0.668 (1.02)</td><td>0.659 (0.562)</td><td>0.657 (0.38)</td><td>0.652 (0.23)</td></tr>
<tr><td rowspan="2">RMS</td><td>Median</td><td><u>0.730 (2.48)</u></td><td><u>0.707 (1.93)</u></td><td>0.688 (1.55)</td><td>0.676 (1.16)</td></tr>
<tr><td>Mean</td><td>0.670 (1.13)</td><td>0.662 (0.82)</td><td>0.661 (0.69)</td><td>0.657 (0.56)</td></tr>
<tr><td rowspan="2">MPH</td><td>Median</td><td><u>0.735 (2.48)</u></td><td>0.687 (1.49)</td><td>0.667 (0.81)</td><td>0.661 (0.55)</td></tr>
<tr><td>Mean</td><td>0.663 (0.82)</td><td>0.657 (0.39)</td><td>0.653 (0.24)</td><td>0.648 (0.08)</td></tr>
<tr><td rowspan="4">Slope</td><td rowspan="2">SV_{2pts}</td><td>Median</td><td><u>0.744 (2.63)</u></td><td><u>0.701 (1.80)</u></td><td>0.671 (1.10)</td><td>0.665 (0.82)</td></tr>
<tr><td>Mean</td><td>0.664 (0.73)</td><td>0.660 (0.46)</td><td>0.657 (0.36)</td><td>0.653 (0.25)</td></tr>
<tr><td rowspan="2">SV_{6pts}</td><td>Median</td><td><u>0.746 (2.64)</u></td><td><u>0.703 (1.83)</u></td><td>0.671 (1.09)</td><td>0.665 (0.81)</td></tr>
<tr><td>Mean</td><td>0.664 (0.73)</td><td>0.659 (0.45)</td><td>0.657 (0.35)</td><td>0.653 (0.24)</td></tr>
</table>

Note: Adjusted R2 before incorporating micro-texture parameters = 0.670

The cells of Table 4, which present underlined values, indicate the cases for which the parameter used to characterize the micro-texture significantly affected the BPN with a 90% confidence level, and the Adjusted R^2 of the estimated model was greater than the reference model. None of the parameters was significant when calculated using the mean approach. Furthermore, the parameters that were significant when calculated using the median became not significant when using the mean for the same baseline. It is also interesting to note that none of the micro-texture parameters significantly affected the BPN when using a baseline of 10 mm or greater. On the other hand, the use of a 1 mm long baseline led to an improved description of the skid resistance with respect to the model using only the macro-texture, regardless of the parameter when calculated using the median.

When comparing the parameters calculated using the median value and a 1 mm baseline, it is observed that the adjusted R^2 of the models using the slope parameters are slightly greater than the ones using the amplitude parameters. This observation implies that characterizing the surface micro-texture using the slope values of the profiles predicts the BPN better than when using the amplitude values. In addition, it is observed that the MPD was the most significant in explaining the BPN among the models using amplitude parameters whereas the summary statistics between the two models with slope parameters were similar to each other.

The highest adjusted R^2 among the models using spatial parameters was 0.746, which is lower than the one obtained using spectral parameters. Therefore, the micro-texture parameters computed in the frequency domain were better in predicting the pavement BPN than the parameters calculated using the spatial coordinates.

5.3 Effect of Accounting for Contact Area on Prediction of Skid Resistance

The polishing effect of traffic on the aggregates of the pavement surface might result in lower micro-texture on the higher points of the surface for some types of aggregates. Since all of the surfaces tested for this study consist of in-service pavement surfaces, additional analyses were performed to determine both whether the values of the micro-texture parameters at the peaks of the profiles differed from the ones at the valleys, and how to better characterize the micro-texture in order to improve the prediction of the skid resistance if that occurs.

5.3.1 Variation of Micro-Texture between Surface's Peaks and Valleys

In order to analyze whether the micro-texture at the peaks of the profiles was different than at the valleys, the micro-texture MPD (using a 1 mm baseline length) was regressed on the corresponding macro-texture mean height value for the segments of each test surface (Equation 9).

$$Micro_{MPD} = \alpha + \beta * Macro_{mean\_height} \quad (9)$$

Where $Micro_{MPD}$ is the set of calculated micro-texture MPD values using a 1 mm baseline, and $Macro_{mean\_height}$ is the set of macro-texture mean height value for the corresponding 1 mm long segments.

The parameters of the linear model (Equation 9) were estimated for each test surfaces using GLS. The t-statistic of the parameter was less than -1.96 for 26 of the 28 tests surfaces of the study, being between -1.96 and 1.96 for the two remaining. Therefore, the micro-texture at the peaks of the surface (active area) was significantly lower than at the valleys for the majority of the tested surfaces.

5.3.2 Spatial Parameters Calculated on Active Area.

Only the micro-texture of the contact area between the vehicle tire and the pavement surface (active area) affects the development of the frictional forces attributed to the micro-texture asperities. Therefore, the use of calculated micro-texture parameters accounting for the active area of the surface is expected to improve the prediction of the skid resistance.

The specification of the models including the micro-texture spatial parameters calculated on the active area was:

$$BPN = \alpha + \beta_{MPD_{macro}} * Macro_{MPD} + \beta_{treat} * Treat + \beta_{treat} * Micro_{param_i}^{ActiveArea} \qquad (10)$$

Where $Micro_{param_i}^{ActiveArea}$ is the set of values for the micro-texture parameters "i" calculated on the active area using the median of the 1 mm long segments for each test surface.

The Adjusted R^2 and the t-statistic of the estimated linear models for each micro-texture parameter are presented in Table 5. The summary statistics of the models using the spatial parameters calculated using the entire profiles are also included in the table for comparison. It can be observed from the table that both the Adjusted R^2 and the t-statistic are greater for the models using the parameters calculated only on the active area. Therefore, accounting for the contact area between the pavement and the vehicle tire improved the prediction of the skid resistance. The highest adjusted R^2 among the models calculated on the active area was 0.776 which is similar to the one obtained using spectral parameters.

Table 5.4: Summary Statistics of the Estimated Models Calculated on the Active Area

Micro-texture Parameters *calculated for*	**Adjusted R2 (t-stat of $\boldsymbol{\beta_{micro}}$)**				
	Amplitude			Slope	
	MPD	RMS	MPH	SV_{2pts}	SV_{6pts}
Entire Profile	0.739 (2.63)	0.730 (2.48)	0.735 (2.48)	0.744 (2.63)	0.746 (2.64)
Active Area	0.763 (3.07)	0.762 (3.01)	0.761 (2.95)	0.772 (3.09)	0.776 (3.14)

Note: Adjusted R2 before incorporating micro-texture parameters = 0.670

Chapter 6. Summary and Conclusions

This study explored different ways to characterize the micro-texture of pavement surfaces with the main objective of quantifying the effect of accounting for both the micro and the macro components of the texture, rather than just the macro-texture, on the prediction of BPN skid resistance. The different methods to characterize the micro-texture were compared in order to determine which one better predicts the skid resistance of the wet pavement surfaces at low speeds.

A total of 28 different pavement surfaces were included in the study, covering a wide range of BPN values, and a number of cases for each possible combination of fine and coarse macro-texture and smooth and sharp micro-texture. Some of the test surfaces were measured after applying a light texturing treatment. The data collection consisted of field measurement of friction and texture performed on the same spot at each the test surfaces. The friction was measured under wet condition of the surface using a BPT, which evaluates the skid resistance of the pavement at lower speeds. The macro-texture was characterized using a CTM, while the micro-texture was characterize by a series of different parameters calculated using the surface coordinates scanned by the LTS.

The following list contains the main conclusions and observations of the study, which apply to the conditions described above:

- The skid resistance at low speeds of the wet pavement surfaces was significantly affected by both the micro- and the macro-texture of the pavement surface.
- Incorporating the characterization of the surface micro-texture to the macro-texture significantly improved the prediction of the pavement skid resistance.
- Among the micro-texture parameters calculated using the frequencies of the micro-texture profile:
    - The intercept of the linearized PSD significantly affected the BPN. The greater the value of the PSD, the greater the low-speed skid resistance of the pavement.
    - The slope of the linearized PSD was found to not significantly affect the low-speed skid resistance, contrary to expectations.

- Among the micro-texture parameters calculated using the spatial coordinates of the entire micro-texture profile:
    - Regardless of the parameter, the prediction of the skid resistance drastically improved when its value for each test surface was calculated using the median of the individual profiles instead of the mean.
    - Regardless of the parameter, the baseline that produced the best prediction of the skid resistance was the 1 mm baseline. None of the parameters significantly explained the BPN when using a baseline of 10 mm or larger.
    - The MPD was the most significant in explaining the BPN among the models using amplitude parameters.
    - Among the slope parameters, the one calculated using six points was similar to the one calculated using two points in the prediction of the BPN.
    - Among the micro-texture spatial parameters, the ones calculated using the slope values of the profiles predicted the BPN better than the ones using the amplitude values.
    - The micro-texture parameters computed in the frequency domain were better in predicting the pavement BPN than the parameters calculated using the spatial coordinates on the entire micro-texture profiles.
- The micro-texture at the surfaces peaks (active area) was found to be significantly lower than at the valleys for the large majority of the tested surfaces.
- Accounting for the contact area between the pavement and the vehicle tire significantly improved the prediction of the BPN. The prediction of the pavement skid resistance using micro-texture spatial parameters calculated on the active area was as good as the one using the spectral parameters.

The authors conclude that accounting for both the macro- and the micro-texture components of the surface will significantly enhance the prediction of BPN of flexible pavements as oppose to accounting solely for the macro-texture component. Such improvement will allow transportation agencies to better manage skid resistance and therefore to improve road safety. Regarding the characterization of the surface micro-texture, the authors strongly recommend accounting for the actual contact area between tire and pavement. In addition, it is recommended to determine the value of the surface micro-texture parameter as the median of the individual segments of analysis using a 1 mm baseline, in order to mitigate the effect of outliers in the texture measurements.

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