

Three-Dimensional Pavement Surface Texture Measurement and Statistical Analysis

By

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List of Symbols

<i>2D</i>	Two-dimensional
<i>3D</i>	Three-dimensional
<i>AC</i>	Asphalt concrete
<i>ADT</i>	Average daily traffic
<i>ANOVA</i>	Analysis of variance
<i>ASTM</i>	American Society for Testing and Materials
<i>BAC</i>	Bearing area curve
<i>BPN</i>	British pendulum number
<i>CTM</i>	Circular track meter
<i>DFT</i>	Dynamic friction taster
<i>DWT</i>	Discrete wavelet transform
<i>ESAL</i>	Equivalent single axle load
<i>FN</i>	Friction number
<i>FT</i>	Fourier transform
<i>HMA</i>	Hot mix asphalt
<i>IRI</i>	International roughness index
<i>LLS</i>	Line-laser scanner
<i>LVR</i>	Low volume road
<i>MnROAD</i>	Pavement test facilities at Minnesota Department of Transportation
<i>MPD</i>	Mean profile depth
<i>MTD</i>	Mean texture depth

N/A	Not available
$NPSE$	Normalized power spectra energy
OFM	Outflow meter
PCC	Portland cement concrete
R^2	Coefficient of determination
RAP	Reclaimed asphalt pavement
RAS	Recycled asphalt shingles
$RMSR$	Root mean square roughness (of 2D texture profile)
SEE	Standard error of the estimate
SFT	Surface friction tester
SI	Sound intensity
S_{ku}	Kurtosis
$SMTD$	Simulated mean texture depth
SPM	Sand patch method
S_q	Root mean square deviation (of 3D texture heights)
S_{sk}	Skewness
VKM	Vehicle kilometre
V_{mc}	Core material volume
V_{mp}	Peak material volume
V_{vc}	Core void volume
V_{vv}	Valley void volume
WFT	Water film thickness
α, β	Regression parameters

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Abstract

Pavement texture has been measured predominantly by using two-dimensional (2D) profile methods although three-dimensional (3D) texture height map methods have been under discussion for many years. The 2D profile based mean profile depth (MPD) is still the well accepted texture index which has been found inadequate to characterize pavement texture especially when tire/pavement friction and noise are involved.

There is a lack of standard 3D texture indices which show strong correlation with pavement friction and noise. Limited information is available to correlate 2D and 3D texture parameters using non-contact methods. There is a need to use 3D texture measurement for more comprehensive understanding of texture. There is a need for in-depth understanding of the relationship between texture and friction.

The objectives of this thesis are to characterize pavement surfaces using 3D texture parameters based on 3D texture measurement and to explore the relationship between 3D texture parameters, pavement friction, and pavement noise.

Field tests are conducted at the following pavement sections for the measurements of texture, friction, and noise.

- Interstate highway I-355 near Joliet, Illinois. Texture was measured by using photometric stereo method and spot-laser circular track meter. A comparison between 3D and 2D texture parameters was conducted. Relationships between 3D macrotexture parameter and pavement friction or noise were explored.
- MnROAD test facilities at Minnesota Department of Transportation, USA. This study compared 3D texture parameters using line-laser scanner with 2D indices using spot-

laser circular track meter.

- Runway of James Armstrong Richardson International Airport (Winnipeg). Texture was measured by using line-laser scanner. Relationships between 3D texture parameter and pavement friction were explored.
- Various municipal streets in Winnipeg (e.g. Manitoba provincial trunk highway (PTH) 8, Ryerson Avenue of Winnipeg). The study evaluated the impact of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) on pavement surface texture.

The findings and contributions of this thesis are:

- The pavement surface texture is measured in a 3D manner by using a line-laser scanner with both horizontal sample interval and vertical accuracy better than 0.05 mm. Texture is also measured by using photometric stereo method and 2D spot-laser based circular track meter for comparison and validation purposes.
- A 3D texture analysis procedure with discrete wavelet transform (DWT) is proposed to separate macrotexture from microtexture and to define texture indices independently.
- Two sets of 3D parameters for macrotextures are proposed and verified by field tests:
 1. the texture amplitude related indices [simulated mean texture depth (SMTD), root mean square deviation (S_q), skewness (S_{sk}), and kurtosis (S_{ku})].
 2. the material volume related indices [peak material volume (V_{mp}), core material volume (V_{mc}), core void volume (V_{vc}), and valley void volume (V_{vv})].
- Normalized power spectra energy (NPSE) is defined as an index for microtexture.

- The relationship between 3D and 2D macrotexture indices [i.e. SMTD and MPD; S_q and root mean square roughness (RMSR)] are established, which is useful for the purposes of data comparison between 3D and 2D methods.
- The relationship is investigated between 3D macrotexture parameters (SMTD and S_q) and pavement friction and noise.
- It is found that texture distribution indices (i.e. S_{sk} and S_{ku}) are significant contributors to pavement friction and noise.
- It is also found that RAP/RAS has positive impact to pavement texture of the tested sections at the time of testing.

The new 3D texture analysis procedure and texture indices proposed in this thesis can be used to characterize various pavement textures (concrete pavement, asphalt pavement, and pavement contains recycled materials) in 3D manner, to compare 3D with 2D texture measurement/indices for quality control purposes, and to evaluate and predict pavement friction and noise.

It is possible to have a better understanding of surface texture, pavement friction, and noise by using combinations of the proposed 3D texture parameters in this thesis.

Chapter 1

INTRODUCTION

1.1 Statement of the Problem

Pavement surface characteristics at the macrotexture and microtexture scale are critical to vehicle stability, traction, friction, and road noise. Highway crash investigations have consistently shown a link between crashes and pavement surface characteristics, such as friction and texture. Thus, there is a need for in-depth knowledge and understanding of the relationship between pavement friction and texture characteristic, so that engineers can develop more effective solutions to potentially hazardous driving conditions.

The cost and complexity of friction and noise testing equipment have hindered some transportation agencies from adopting friction and noise testing. As a result, deficient road surfaces could remain in service for years without being inspected appropriately. There are three significant needs in this area:

1. Current technologies for macrotexture evaluation rely on two-dimensional (2D) methods or volumetric methods. There is a need for three dimensional (3D) non-contact method to recover pavement surface topography (or texture height map).
2. Current texture standards rely on a mean profile depth (MPD) which is a 2D indicator of surface texture. MPD is based on 2D texture profile with distance along the pavement surface as one dimension and the texture elevation as the second. MPD itself is not adequate to represent the texture because it averages 2D texture profile and discards potentially useful information about the surface (texture distribution, for instance). There is a need for 3D texture indicators that are based on 3D texture height map with distance along the pavement surface as one dimension, and the distance

perpendicular to dimension one as the second dimension, and the texture elevation as the third.

3. There is a need for designing road surface texture considering the seasonal variations in temperature, impact of snow or ice, and wet pavement conditions.

1.2 Background

Pavement friction is one of the key elements required to ensure safe operation of vehicles on highways and streets. Empirical evidence suggests that vehicle crash rates are highly correlated to the level of pavement friction available between a vehicle tire and a pavement surface (Hall et al., 2009b, Rizenbergs et al., 1972, Wallman and Astrom, 2001, Rizenbergs et al., 1976). According to the Federal Highway Administration (FHWA, 2015), in 2013, there were 18,257 fatalities as a result of roadway departure crashes, which was 56% of the traffic fatalities in the United States. Based on a study performed in New York, it was reported (Neuman et al., 2003) that low skid resistance increases crash risk on wet pavement by 50%. It is reported that 70% of wet pavement crashes can be prevented or minimized by improving pavement friction (Swanlund and Cheung, 2013).

1.3 Hypothesis of the Study

Pavement texture can be measured and analyzed in 3D manner such that pavement friction and noise can be assessed more adequately than using currently well adopted 2D profile based methods or traditional volumetric methods.

1.4 Objectives of the Study

Texture is the key factor in many pavement surface characteristics. Based on 3D texture measurement instead of the currently used 2D texture profile method, the objectives of this study are:

1. To describe the texture using 3D indicators. Various 2D indicators were utilized to describe pavement texture, e.g. MPD. The problem is that it is lacking a few well accepted indicators which show strong correlation with pavement performance characteristics e.g. friction or noise. This research investigates 3D pavement texture indicators to eventually replace the less representative 2D texture indices. Based on literature review and the practices of texture measurement both in pavement engineering and mechanical engineering, the 3D texture parameters investigated in this thesis can be put into the following groups.

- Texture amplitude indicators

The amplitude indicators are derived from the 3D texture height map of the pavement surface. These indicators include simulated mean texture depth, average roughness, and peak to valley height.

- Statistical indicators

These indicators are also related to the amplitude of the 3D texture height map. These parameters include second, third, and fourth moment of surface texture heights in a representative surface area (such as: root mean square deviation, skewness, and kurtosis).

- Functional indicators

Defined by ISO 13565-2 (1996a), these parameters are derived from area bearing ratio curve which is also based on the 3D texture height map. These indi-

cators include peak material volume, core material volume, core void volume, and valley void volume.

- Spectral indicators

These parameters derived from spectral analysis of the 3D texture height map. The purpose of these parameters is to identify the presence or significance of various repeating features of texture.

2. To apply 3D pavement texture indicators. The research recommends appropriate 3D texture indicators to classify and identify various pavement textures. The recommended indicators are correlated to pavement performance characteristics e.g. friction and noise. By applying these indicators, it is possible to identify the contributing factors and quantify their impacts on tire/pavement friction and noise. The results also allow for investigating the reasons of traffic accidents.

Many texture measuring methods are currently available of which most are 2D based methods which are not adequate to represent the pavement texture. This research focuses on measuring and recovering pavement texture using 3D methods. In addition, pavement texture is measured in three aspects: (1) the depth, texture amplitude of the measured area; (2) the frequency, texture spectra with various wavelengths; (3) the distribution of texture, the topography of the measured area, skewness and kurtosi of the texture height maps, for instance. Table 1.1 is comparing the 2D method with 3D method for texture measurement.

1.5 Significance of the Study

As shown in Table 1.2, various methods are available to measure pavement texture. These methods provide primarily mean texture depth (MTD), mean profile depth (MPD), or root mean square roughness (RMSR). These indices can be used to distinguish a rough surface

Table 1.1: Advantages and disadvantages of 2D and 3D texture measurements.

Method of measurement (Texture map dimensions)	Texture Indices	Advantages	Disadvantages
2D texture profile method (e.g. Circular track meter)	• Mean profile depth (MPD) • Root mean square roughness (RMSR)	• ASTM standard available • Widely used method • Correlates well with mean texture depth (MTD) from sand patch method • Ample researches and documentation available	• Using only a single profile to represent surface area texture • 2D texture indices are only estimate of 3D texture depth • 2D texture indices are insufficient to represent pavement/tire interaction • Focus on macrotexture
3D texture height map method (e.g. line-laser scanner)	• Simulated mean texture depth (SMTD) • root mean square deviation (S_q) • Skewness, Kurtosis • Material volume, void volume • Normalized power spectra energy	• To recover texture in 3D manner to represent surface area • More texture indices available • To simulate possibly pavement/tire interaction using finite element analysis	• No standard to follow • Newer method with inadequate research or practices

to a smooth surface, but are not able to represent surface characteristics in 3D feature. In addition, these indicators themselves were not found to have a strong correlation with pavement friction or noise.

Table 1.2: Methods for pavement texture measurement.

Types	Features	Methods	Index	Standard
Low speed (Stationary)	Need lane closures	Sand patch	Mean texture depth (MTD)	ASTM E 965
		Outflow meter	Outflow time	ASTM E 2380
		Circular track meter	Mean profile depth Root mean square roughness	ASTM E 2157
High speed	Highway speed Non-contact	Road surface analyzer (ROSANv)	Mean profile depth	No standard

Surface texture is the key feature to affect pavement friction and noise. Researchers have carried out studies to explore the relationship between pavement texture and friction so that engineers can develop effective solutions to potentially hazardous situations (Hall et al., 2009b). However, there is still not a well accepted method to address this issue. El Gendy (2008) pointed out that 2D indicators are insufficient to represent texture, especially

when friction or noise are studied because it is an area instead of a single line for the contact between a tire and the pavement . There is a need for 3D analysis of pavement surface texture.

This research measures and recovers pavement surface texture by using photometric stereo method and line-laser scanning method. These texture measurements are processed and represented by 3D parameters.

This research optimizes the use of possible methods to recover various types of pavement types, highways, municipal streets, and airport runways for both asphalt concrete (AC) and Portland cement concrete (PCC) pavement.

Regression analysis is also carried out between the proposed texture indices and pavement friction or pavement noise.

The findings of this research offer not only the possibility to recover pavement texture in 3D feature, but also provide improved pavement texture classification. The application of these indices is anticipated to have a positive impact on pavement characteristic and safety analysis.

In summary, the significance of this study is related to the followings:

- Surface texture is an important pavement property and needs to be fully understood.
- There is a lack of standard 3D indicators to represent texture characteristics.
- The relationship between 3D texture indices and pavement friction or noise should be characterized and understood.
- Potentially 3D texture parameters may contain additional information about the surface, performance and safety indices that are not available using 2D parameters.
- Better understanding and practices could be achieved for pavement evaluation and construction.

Chapter 2

LITERATURE REVIEW

2.1 Pavement Surface Texture

2.1.1 Definition of Pavement Texture

Pavement surface texture is defined as the deviation of a pavement surface from a flat surface within a specified wavelength range. As shown in Table 2.1, pavement texture can be grouped into four categories based on wavelengths: microtexture, macrotexture, megatexture, and unevenness (ASTM E1845, 2009, ISO 13473, 1997).

Table 2.1: Four categories of pavement surface texture.

Texture classification	Relative wavelengths (λ)	Sources of texture
Microtexture	$\lambda < 0.5 \text{ mm}$	Fine sand or surface roughness of aggregate
Macrotexture	$0.5 \text{ mm} \leq \lambda < 50 \text{ mm}$	Space and depths between aggregate particles
Megatexture	$50 \text{ mm} \leq \lambda < 500 \text{ mm}$	Construction or pavement distress
Unevenness (roughness)	$0.5 \text{ m} \leq \lambda < 50 \text{ m}$	Construction or pavement distress

Pavement texture can be characterized by texture amplitude and wavelength in a pavement surface. The surface texture ranges from the submillimetre roughness contained in individual aggregate particle to a span of unevenness in the range of meters in length. The two levels of texture that are predominantly important for traffic safety are microtexture and macrotexture (Henry, 2000, Hall et al., 2009b), as shown in Figure 2.1.

- Microtexture is the degree of roughness of individual aggregate particles. They are the fine texture that interact with tire rubber for friction. Microtexture is mainly responsible for pavement friction at low speeds and dry pavement condition.

- Macrotexture is the degree of roughness due to the deviations among particles. Macrotexture is mainly responsible for reducing the potential for separation of tire and pavement surface due to hydroplaning and for inducing friction caused by hysteresis for vehicles traveling at high speed. It accounts for over 95% of the friction when the speed is 105 km/h or higher (Hall et al., 2009b). Macrotexture also allows tire to contact the surface when pavement is wet.

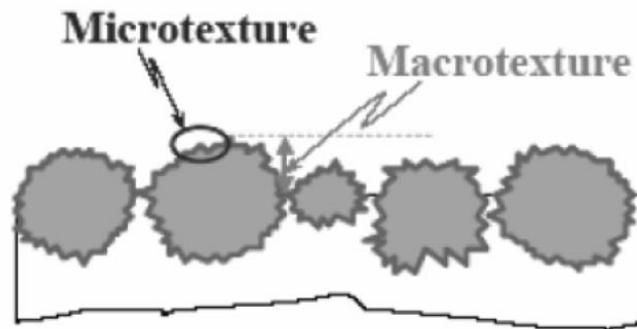


Figure 2.1: Microtexture versus macrotexture (Flintsch et al., 2003a).

2.1.2 Pavement Texture Measurement

Pavement texture can be measured either by stationary methods which need lane closures or at highway speed without lane closures.

The established stationary texture measurement methods include: the sand patch method (ASTM E965, 2006), the outflow meter (ASTM E2380, 2009), and the circular track meter (ASTM E2157, 2009).

Sand Patch Method (SPM)

The SPM assesses only pavement surface macrotexture through the spreading of a known volume of glass beads in a circle onto a cleaned surface of pavement to measure, as



Figure 2.2: Sand patch method to measure macrotexture depth (Yaacoba et al., 2014).

shown in Figure 2.2, the diameter of the resulting circle. Texture index, the mean texture depth (MTD), is defined as the result of the volume divided by the area of the circle.

Outflow Meter (OFM)

The OFM measures the water drainage time through surface texture and the interior voids of pavement. The OFM indicates the hydroplaning potentiality of a surface by relating to the escape time of water beneath a moving tire (ASTM E2380, 2009) . The major parts of the OFM are: a cylinder with a rubber ring on the bottom and an open top, sensors measure the time required for a known volume of water to pass under the seal or into the pavement. Outflow time of the water is reported as an indicator of pavement macrotexture. The rougher the pavement macrotexture is the shorter the outflow time will be, and vice versa.

Circular Track Meter (CTM)

The CTM uses a spot-laser to measure pavement surface profile along a 286 mm diameter circular path of the pavement surface at intervals of 0.87 mm. The spot-laser

arm rotates at 6 m/min and generates profile traces of the pavement surface. The profile is then divided into 8 segments for texture parameter calculation. Two different macrotexture indices can be computed from this profile: mean profile depth (MPD) and root mean square roughness(RMSR) as specified in ASTM E2157 (2009).

Alternatively, pavement surface texture can also be measured by using high-speed methods.

Road Surface Analyzer (ROSAN)

ROSAN (1997) is a portable, vehicle-mounted, automated system for the measurement of pavement texture at highway speeds along a linear path. A spot-laser measuring unit is mounted onto the front bumper of a vehicle which can travel at highway speeds. The system calculates both MPD and estimated mean texture depth.

In recent years, some newer methods are available to measure and recover pavement texture in three-dimensional (3D) manner. The measurement of texture in a 3D manner will be discussed in section 2.2

2.1.3 Pavement Surface Texture Indicators

In transportation engineering, pavement surface texture measurement is dominantly based on the surface profile method which is achieved by measuring a line along traffic direction and representing that line mathematically as a height function. Current pavement texture indices are based mainly on 2D texture profile although researchers have been trying to recover the pavement texture in 3D manner in recent years (Rasmussen et al., 2011b).

The most common and well established 2D texture parameters in pavement engineering are:

- Mean Texture Depth (MTD): The average pavement macrotexture depth obtained from sand patch method.

- Mean Profile Depth (MPD): The average of the 2D profile depth based on 100 mm profile length (baseline) as calculated in Equation (2.1).

$$MPD = \frac{PeakLevel1 + PeakLevel2}{2} - AverageLevel \quad (2.1)$$

Where

- MPD = mean profile depth based on 100 mm profile length (baseline),
- $PeakLevel1$ = peak texture elevation of the first half (50 mm) of the baseline,
- $PeakLevel2$ = peak texture elevation of the second half (50 mm) of the baseline,
- $AverageLevel$ = the averaged texture elevation of the 100 mm baseline.

- Estimated Texture Depth (ETD): The estimated MTD from the MPD.
- Root Mean Square Roughness (RMSR): the standard deviation of the heights of the surface (2D texture profile), is a texture indicator used to assess the average variation of a pavement surface texture. The calculation of RMSR is shown in Equation (2.2).

$$RMSR = \sqrt{\frac{1}{N} \sum_{i=1}^N z_i^2} \quad (2.2)$$

Where

- $RMSR$ = calculated root mean square roughness based on 100 mm baseline,
- N = number of discrete points along 100 mm profile length (baseline),
- z_i = height of surface profile from the mean profile level at position of i .

In the manufacturing industry, however, more advanced techniques have been developed from the analysis of areal surface topography. Functional information about the surface can be gained by analyzing the 3D surface texture height map. A few sets of 3D texture parameters have been developed.

As can be seen from Figure 2.3, the first set of 3D texture parameters were the so-called Birmingham 14 parameters which were resulted from a European program between 1990 and 1993 (Stout, 2000). The Birmingham 14 parameters were well accepted as a big

achievement. However, they were considered to be more theoretical than practical due to the lack of meaningful practice and industrial application (Lonardo et al., 1996).

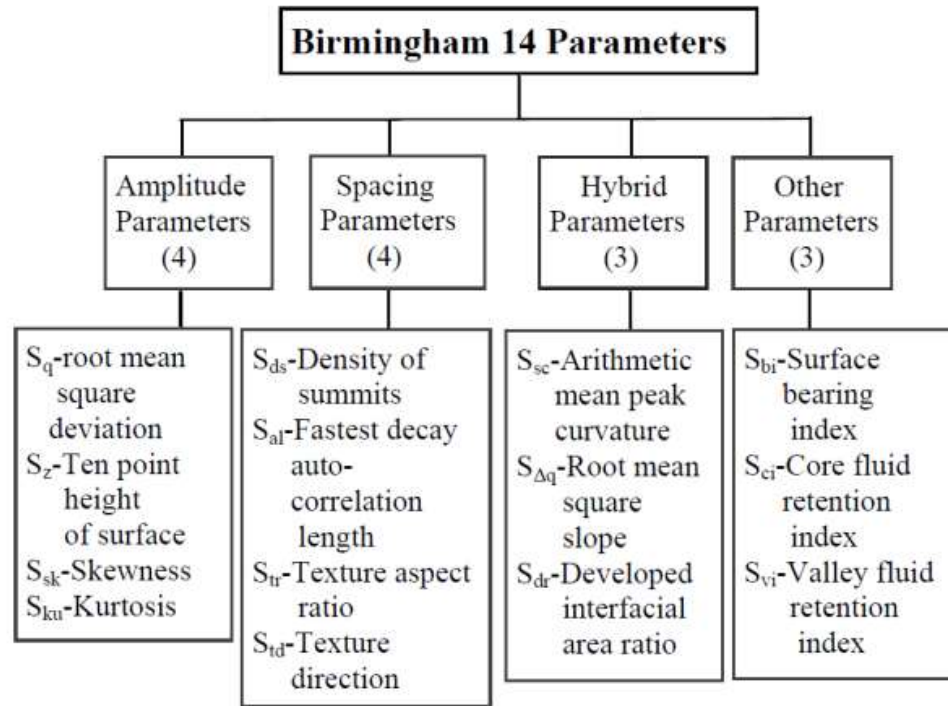


Figure 2.3: The Birmingham 14 3D texture parameters (Stout, 2000).

From 1998 to 2001, the International Standard Organizations carried out another research project: SURFSTAND which provided the core part of the new basis for 3D surface texture standards (Blunt and Jiang, 2003). The field 3D parameters includes the S-parameter and the V-parameter, as shown in Figure 2.4 and Figure 2.5, respectively. The S-parameters describe texture height amplitude and spatial information (spacing frequency), while the V-parameter give texture information based on a material ratio curve (Abbott-Firestone curve) (Whitehouse, 2010).

It is not always necessary to employ all the 3D parameters discussed above to characterize surface texture (Blunt and Jiang, 2003). The adopted and updated 3D texture parameters in this research will be discussed in chapter 3 for the evaluation of pavement

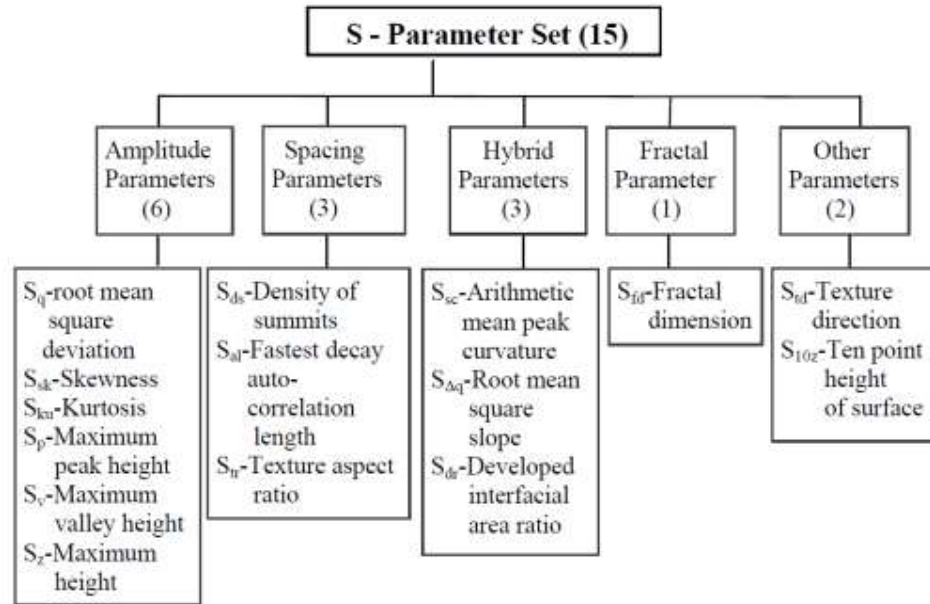


Figure 2.4: The 3D texture S-parameter set (Blunt and Jiang, 2003).

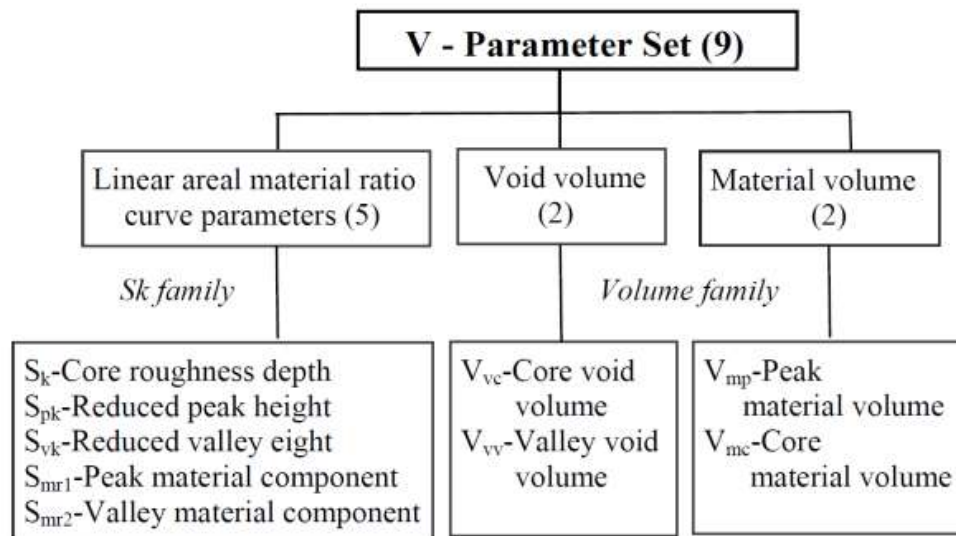


Figure 2.5: The 3D texture V-parameter set (Blunt and Jiang, 2003).

surface texture in transportation engineering.

2.2 3D Pavement Texture Measurement

3D texture measurement can be achieved by using the photometric stereo method or the line-laser scanning method.

2.2.1 Photometric Stereo Method for 3D Texture Measurement

The photometric stereo method which assumes orthographic projection was proposed by Woodham (1980) and has been used by many researchers (Coleman and Jain, 1982, McGunnigle, 1998, Gullon, 2003). In the photometric stereo method, the recovered shape is expressed in terms of the surface gradient (p, q) , and a height recovery from surface gradient can be carried out by using either local integration or global integration.

For the photometric stereo method, it is to get three images under three different directions of incident illuminations. The viewing direction (camera location) is held constant when the three images are taken. Assuming a constant light intensity, the reflected intensity at any point (x, y) is a function of the three unknowns, p , q , and ρ (the albedo, a reflectance factor that represents the proportion of light reflected with respect to the incident light.). Since the image geometry is not changed, any three incident directions which do not lie in a plane would provide sufficient information to determine p , q , and ρ at each point (x, y) (El Gendy, 2008).

Coleman and Jain (1982) extended the photometric stereo technique of Woodham to a four-source photometric technique with the goal of overcoming specular distortion. Although three light sources are sufficient to recover a surface, the fourth source provides redundancy and it can be used to detect and correct specular effects.

McGunnigle (1998) used a simple photometric stereo algorithm that avoids matrix

inverse calculations by placing the lights with a constant zenith angle and 90° increments in the azimuth angles.

As can be seen from Figure 2.6, the Pavement Group at the University of Manitoba (El Gendy, 2008) developed a device to retrieve the pavement texture by using photometric stereo technique. The entire system is enclosed in a covered box that isolates the sample from the ambient light. It takes about 1–2 minutes to conduct a complete measurement (4 images) of surface texture at one measure spot.

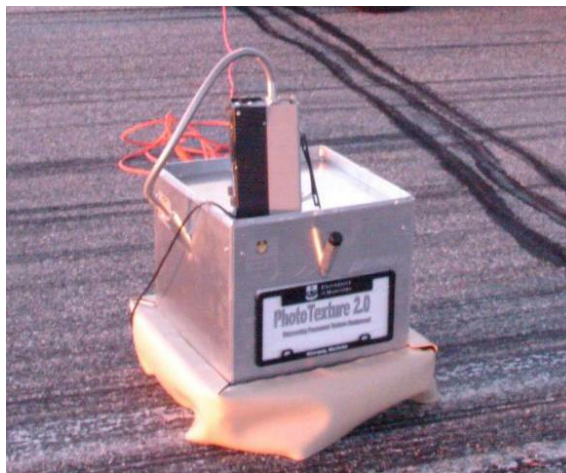


Figure 2.6: A photometric stereo texture measuring device.

The framework for characterizing pavement texture using the photometric stereo device is shown in Figure 2.7.

2.2.2 Line-Laser Scanning Method for 3D Texture Measurement

Laser scanning technique has been introduced to measure the pavement macrotexture in recent years (Wang et al., 2010). Most laser profile equipment in use today measures texture with a spot-laser to create a 2D texture profile with the travel direction as one dimension and the texture height as the other dimension. The 2D profile fails to completely describe characteristics of texture that are important to many surface features (Rasmussen et al.,

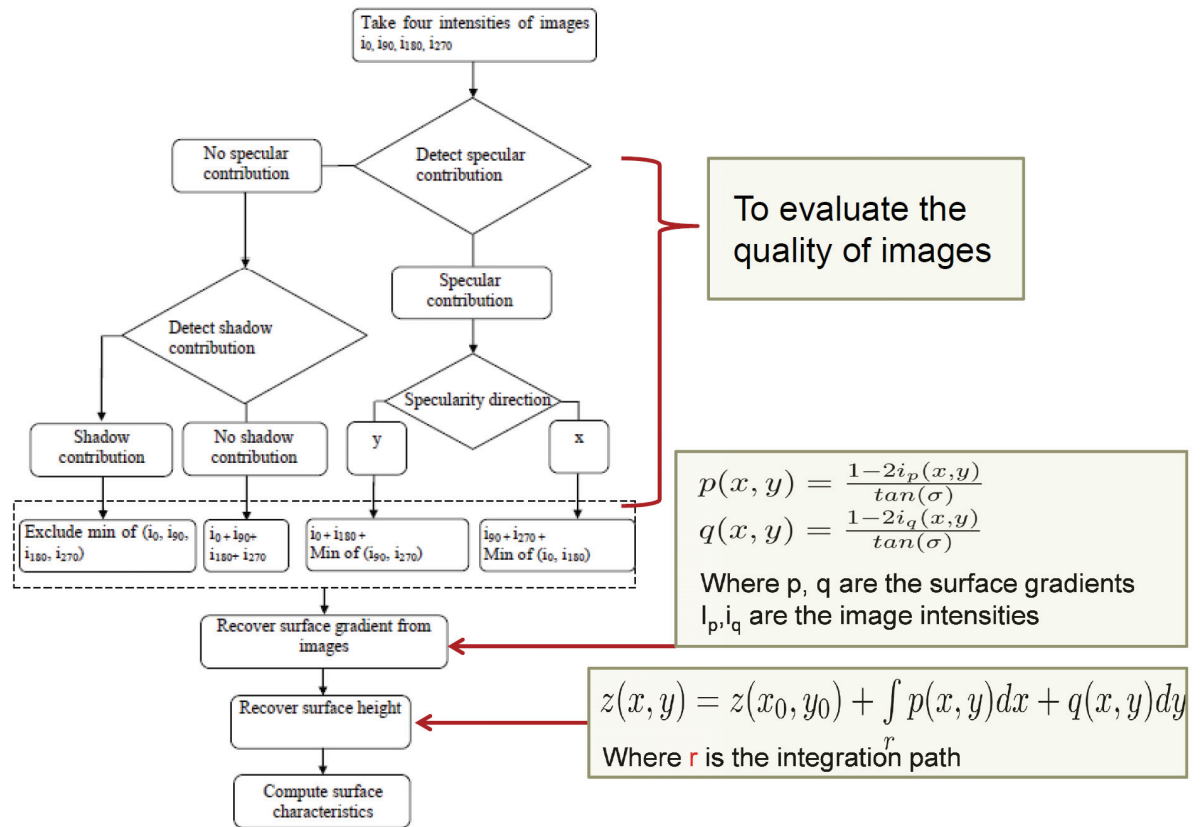


Figure 2.7: Framework of photometric stereo method for texture measurement (El Gendy, 2008).

2011b). Also, 2D profile is not representative of the real pavement surface because the tire footprint is an area instead of a single line.

To overcome the limitation of using a spot-laser sensor, a line-laser can be used to have a 3D texture height map (topography) with the distance along the travel direction (longitudinal direction) as one dimension, the distance perpendicular to the travel direction (transverse direction) as the second dimension, and the texture height as the third dimension.

RoboTex Line-laser Scanner

As shown in Figure 2.8, a robotic-based texture measurement system (RoboTex) was developed in 2005 (Rasmussen et al., 2011b). RoboTex consists of four major parts: line-laser sensor to scan the pavement, a platform to mobilize the laser line, digital imaging system, and data processing software. Figure 2.9 shows the measure principle of line-laser scanning technique, while Figure 2.10 shows the recovered pavement texture sample by using RoboTex.

RoboTex is able to collect 100 or more texture points along a 100 mm wide laser line at transverse direction as it moves at a speed of 0.5 m/s along the travel direction. Since MPD can be calculated for each and every profile in the transverse direction, continuous MPD is achievable while the RoboTex is moving in travel direction.

LS-40 Line-Laser Pavement Surface Scanner

As can be seen from Figure 2.11, based on the laser triangulation principle (Acosta et al., 2006), a 3D pavement texture measurement system, LS-40 line-laser pavement surface scanner, is developed by Measurement Instrument Technology (HyMIT, 2013). Figure 2.12 presents a picture of the equipment with a laptop sitting on the top of the scanner.



Figure 2.8: RoboTex texture measurement system (Rasmussen, 2010).

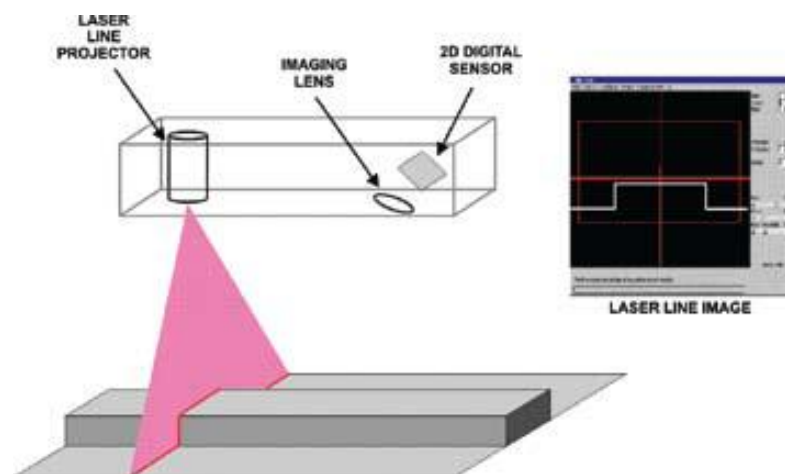


Figure 2.9: Measure principle of RoboTex (Rasmussen et al., 2011b).

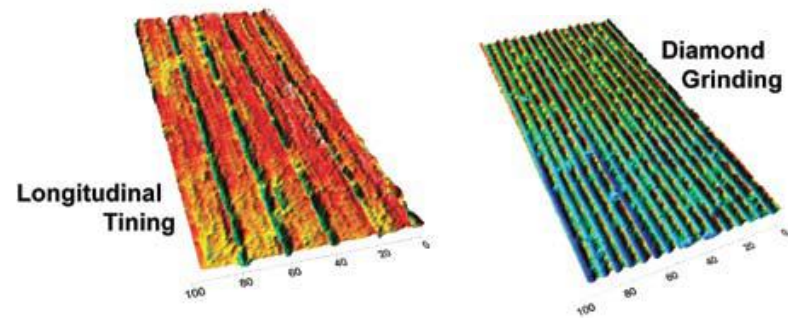


Figure 2.10: Recovered pavement texture sample by RoboTex (Rasmussen et al., 2011b).

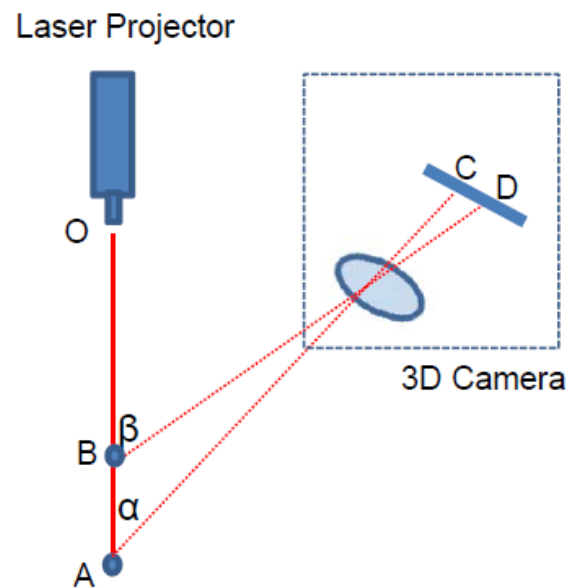


Figure 2.11: Principle of laser triangulation in elevation measurement (Acosta et al., 2006).

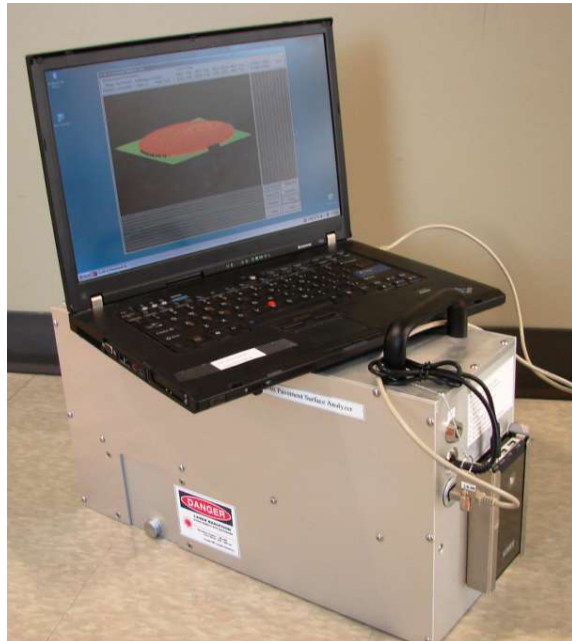


Figure 2.12: A LS-40 line-laser pavement surface scanner.

The LS-40 line-laser scanner (HyMIT, 2013) is a battery operated pavement surface measurement and analysis instrument. A built-in motor stage moves a very fine laser beam over target surface. A high resolution camera takes laser beam images from an angle. Laser triangulation algorithm is used to process these images for texture heights measurement. Results are presented as numerical data which can be stored in a computer for further analysis.

Using a line-laser, LS-40 can scan and create a line profile of the target surface (perpendicular to the traffic direction, or in transverse direction thereafter) at one time. Such a profile contains 2448 data points and covers 100 mm of the surface, which gives the resolution in the transverse direction as $100/2448 = 0.041$ mm per data point. The LS-40 has the ability to scan up to 254 mm at single measurement in traffic direction or longitudinal direction with 5120 transverse profiles, which makes the resolution in longitudinal direction as $254/5120 = 0.050$ mm per data point. In summary, the LS-40 can create a 3D surface texture height map covering an area of 100 mm $\times$ 254 mm with 2448 $\times$ 5120 data points.

The measured surface height map is saved into three data sets to facilitate calculations of the surface parameters. The first data set covers a distance from 0 to 102 mm longitudinally, the second set covers a distance from 102 to 204 mm, and the third covers a distance from 152 to 254 mm. There is an overlap of 51 mm between data sets 2 and 3.

2.2.3 Summary of Various Texture Measuring Methods

Table 2.2 provides a summary of various 2D and 3D methods for texture measurement modified from Hall et al. (2009b).

Table 2.2: Advantages and disadvantages of various 2D and 3D texture measuring methods modified from Hall et al. (2009b).

Test Method/Equipment	Associated Standard texture Indices	Advantages	Disadvantages
Sand Patch Method (SPM)	ASTM E 965 ISO 10844 Mean texture depth (MTD)	- Simple and inexpensive methods and equipment - When combined with other data, can provide friction information. - Widely used method	- Method is slow and requires lane closure - Only represents a small area - Only macrotexture is evaluated - Sensitive to operator variability - Labor intensive activity
Outflow Meter (OFM)	ASTM E 2380 Outflow time	- Simple methods and relatively inexpensive equipment - Provides an indication of hydroplaning potential in wet weather	- Method is slow and requires lane closure - Only represents a small area of the pavement surface - Output does not have a good correlation with MPD or MTD
Circular Track Meter (CTM)	ASTM E 2157 Mean profile depth (MPD), Root mean square roughness (RMSR)	- Measures same diameter as Dynamic friction tester, allowing texture/friction comparisons. - Repeatable, reproducible, and independent of operators - Correlates well with MTD. - Measures positive and negative texture - Is small (13 kg) and portable - Setup time is short (less than 1 minute)	- Method is slow (about 45 seconds to complete) and requires lane closure - Represents a small surface area
3D texture height map method (e.g. line-laser scanner)	Research device Simulated mean texture depth (SMTD), root mean square deviation (S_q), Skewness, Kurtosis, material volume, void volume, and normalized power spectra energy	- To recover texture in 3D manner to represent surface area - More texture indices available - To simulate possibly pavement/tire interaction using finite element analysis	- No standard to follow - Newer method with inadequate research or practices
Highway speed method (e.g. road surface analyzer (ROSAN))	ASTM E 1845 ISO 13473 MPD and Estimated mean texture depth (EMTD)	- Collects continuous data at high speeds - Correlates well with MTD - Can be used to provide a speed constant to accompany friction data	- Equipment is very expensive - Skilled operators are required for collection and data processing

2.3 Pavement Surface Friction

2.3.1 Definition of Pavement Friction

Pavement surface friction is defined as the force that resists the relative motion between a vehicle tire and the surface of a pavement. As a tire rolls or slides over a pavement surface, a resistive force is generated as shown Figure 2.13 (Hall et al., 2009b).

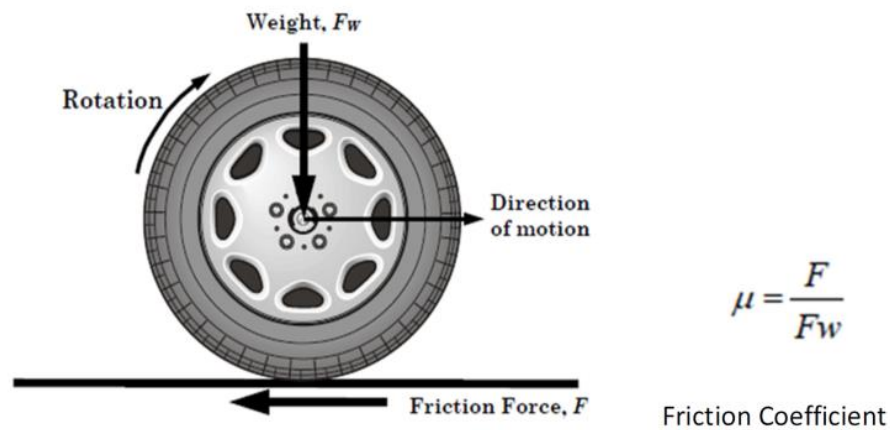


Figure 2.13: Friction forces for a rotating wheel (Hall et al., 2009b).

The coefficient of friction between a tire and the pavement is different at different slip percentage, as shown in Figure 2.14 (Henry, 2000). As can be seen from Figure 2.14 (Henry, 2000), the coefficient of friction reaches its peak value at the critical slip between 10% and 20% slip rate after a rapid increase. After the critical slip, the friction decreases to a value known as the coefficient of sliding friction at 100 % slip. Research found that the difference between the peak and sliding coefficients of friction can be up to 50% of the sliding value, and is much worse on wet pavements than on dry pavements (Henry, 2000).

The lateral or side-force friction is another important aspect of friction. The lateral friction occurs when a vehicle is changing direction or compensating for pavement cross-slope and cross wind effects (Hall et al., 2009b).

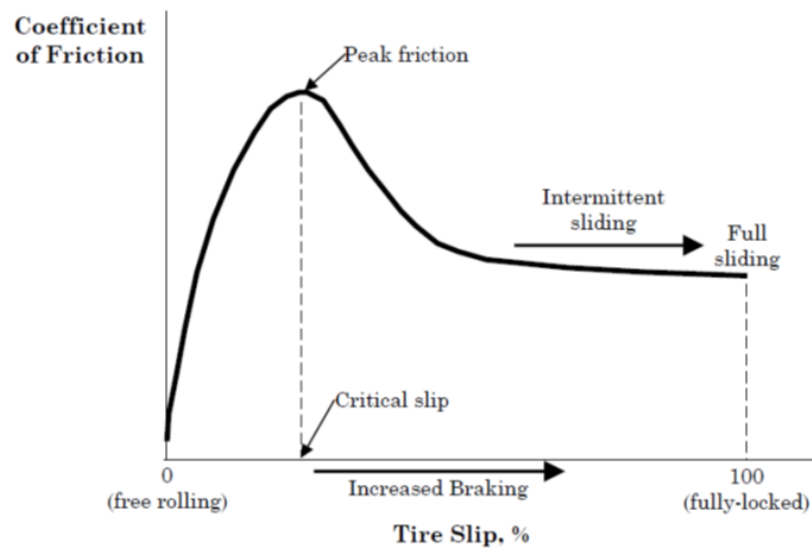


Figure 2.14: Pavement friction versus tire slip (Henry, 2000).

As can be seen from Figure 2.15, pavement friction is the result of a combination of two principal frictional force components: adhesion and hysteresis.

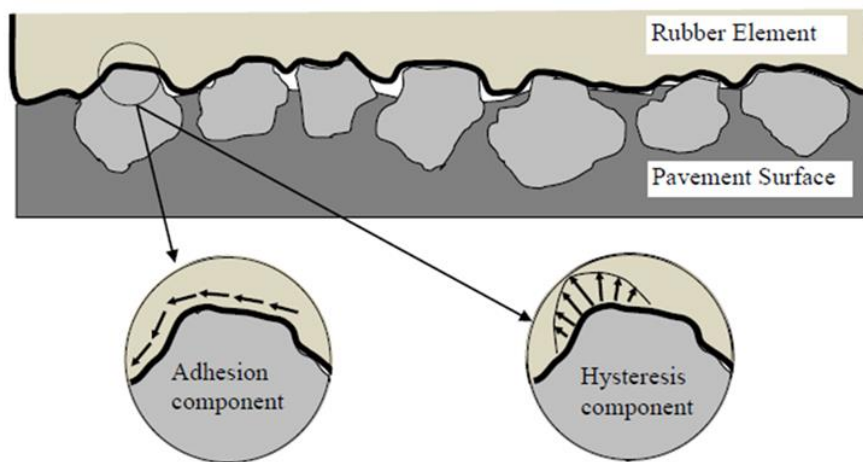


Figure 2.15: Frictional force components: adhesion and hysteresis (Hall et al., 2009b).

- Adhesion is a function of the interface shear strength and contact area between tire and pavement surface as they come into contact with each other. The small-scale interlocking of the vehicle tire rubber and the pavement texture is the key factor to

tire/pavement adhesion.

- Hysteresis comes from the energy loss due to the deformation of the vehicle tire to pavement asperities and surface texture at the contact area.

The characteristics of microtexture of the aggregate particles contained in the pavement dominate the available adhesion force, while the features of macrotexture are the main contributors to hysteresis force (Hall et al., 2009b). Adhesion is especially important at low speeds although it is a necessary component at any speeds (Rasmussen et al., 2007). On wet and rough-textured pavements, hysteresis is the dominant component of the friction (Hall et al., 2009b).

Adhesion and hysteresis depend on the following factors (Hall et al., 2009b):

- pavement surface characteristics.
- the contact between tire and pavement.
- the properties of the tire, and
- temperature and sliding speed since tire rubber is a visco-elastic material.

2.3.2 Measurement of Pavement Friction

Many different types of equipment have been developed to measure pavement friction, and their differences can be significant (Hall et al., 2009b). To facilitate friction measurement and data analysis, the American Society for Testing and Materials and American Association of State Highway and Transportation Officials have developed several surface characteristic standards and measurement protocols.

Locked-wheel Skid Tester

A common method for measuring pavement friction is the locked-wheel method (ASTM E274, 2011). This method is to test the frictional properties of the surface under full sliding for a vehicle without anti-lock brakes to simulate the emergency braking conditions. As indicated by its name, locked-wheel, the test wheel is locked and unable to rotate. During the locked-wheel test, the vehicle speed is equal to slip speed (Henry, 2000). The results of the locked-wheel test are reported as a friction number (FN) or skid number (SN). The test vehicle with one tire locked usually operate at speeds between 65 km/h and 100 km/h using either a smooth (ASTM E524, 2011) or ribbed tire (ASTM E501, 2008). The tread of a ribbed tire is helpful to drain water away from the underneath of the test tire and make the rubber contact with microtexture. As a result, the ribbed tire is insensitive to the pavement surface water film thickness; thus it is sensitive to the pavement microtexture. In contrast, the smooth tire is sensitive to macrotexture (Hall et al., 2009b).

Fixed Slip Devices (Griptester, Dynatest HFT 6875)

Fixed-slip devices measure the friction experienced by vehicles with anti-lock brakes. Fixed-slip devices maintain a constant slip, typically between 10 % and 20 %, as a vertical load is applied to the test tire (Henry, 2000). These devices are able to measure the peak friction at critical slip condition. The two most common fixed-slip devices are Griptester (de Solminihac et al., 2008) and Dynatest HFT 6875 (Dynatest 6875, 2013). These devices are more sensitive to microtexture because of the low slip speed.

Side Force Method

The side-force method (ASTM E670, 2009) measures the ability of vehicles to maintain control in curves and involves maintaining a constant angle between the tire and the direction of motion. The two most common side-force measuring devices are the Mu-Meter and the Side-Force Coefficient Road Inventory Machine (SCRIM) (Hall et al., 2009b).

British Pendulum Tester

The British Pendulum Tester produces a low-speed sliding contact between a standard rubber slider and the pavement surface. The elevation to which the arm swings after contacting the surface texture provides an indicator of the frictional properties. The higher the elevation of the arm, the smoother the pavement surface. Data from five readings are typically collected and recorded by hand (ASTM E303, 2008). British Pendulum number (BPN) is reported as the friction indicator.

Dynamic Friction Tester

The Dynamic Friction Tester measures the torque needed to rotate three small, spring-loaded, rubber pads in a circular path over the pavement surface at various speeds. Water is applied at 3.6 L/min during testing. Rotational speed at 20, 40, 60, and 80km/h, rotational torque corresponding to various speeds, and downward load are measured and recorded for the analysis of friction-speed relationship. (ASTM E1911, 2009).

Summary of Various Pavement Friction Test Methods

Table 2.3 provides a summary of various methods for pavement friction measurement modified from Hall et al. (2009b).

2.3.3 Factors Affecting Available Pavement Friction

The factors that influence pavement friction forces are summarized in Table 2.4. Pavement friction is always changing with various combinations of these factors. Hence, friction is a process instead of an inherent property of the pavement (Hall et al., 2009b).

Microtexture and macrotexture, pavement material properties, and slip speed are the factors on which highway agencies have certain control (Hall et al., 2009b). Since the effect

Table 2.3: Advantages and disadvantages of various methods for pavement friction measurement modified from Hall et al. (2009b).

Test Method/Equipment	Associated Standard texture Indices	Advantages	Disadvantages
Locked-Wheel Skid Tester	ASTM E 274 Friction number (FN) or skid number (SN)	- Well developed and very widely used method in the U.S. - Systems are user friendly, relatively simple, and not time consuming.	- Can only be used on straight segments (no curves, T-sections, or roundabouts). - Can miss slippery spots because measurements are intermittent
Fixed Slip Devices (e.g. Griptester, Dynatest HFT 6875)	Various standards Friction is reported as FN	Continuous, high resolution friction data collected.	- Take readings at a specified slip speed - Their slip speeds do not always coincide with the critical slip speed value, especially over ice- and snow-covered surfaces. - Uses large amounts of water in continuous mode - Requires skillful data reduction
Side Force Method	ASTM E 670 Mu Number, $M_{\mu N}$, or the sideways force coefficient, SFC.	- Well controlled skid condition similar to fixed-slip device results. - Measurements are continuous throughout a test pavement section - Method is commonly used in Europe	- Very sensitive to road irregularities (potholes, cracks, etc.) which can destroy tires quickly - Mu-Meter is primarily only used for airports in the U.S.
British Pendulum Tester	ASTM E 303 British Pendulum Number (BPN)	- Is used worldwide as a measure of friction and texture - Suitable for both laboratory and field evaluation - Can be used to measure both longitudinal and lateral pavement/tire friction	- BPN variability is large and can be affected by operator procedures and wind effects - Traffic control is required - Collect only spot measurement - Multiple measurements must be made over the length of the section
Dynamic Friction Tester	ASTM E 1911 DFT numbers or friction coefficients, and International Friction Index (IFI), designated by F(60) and SP.	- Can be used for field and laboratory testing for quality control/quality assurance (QC/QA), project, and investigatory friction data collection. - Measures same diameter as circular track meter, allowing texture/friction comparisons.	- Traffic control is required - Collect only spot measurement - Multiple measurements must be made over the length of the section

of surface texture characteristics is one of the objectives of this study, it will be discussed in next chapters of this thesis. The effect of environmental factors, pavement distress, and tire properties are discussed briefly as follows:

Table 2.4: Factors affecting available pavement friction (Hall et al., 2009b).

Pavement surface characteristics	Vehicle operating parameters	Tire properties	Environment
Microtexture*	Slip speed*	Foot print	Climate
Macrotexture*	1.Vehicle speed,	Tread design and	1.Wind
Megatexture/	2.Braking action	Condition*	2.Temperature*
unevenness	Driving maneuver	Rubber composition	3.Water (rainfall, condensation)*
Material properties*	1.Turning	and hardness	4.Snow and ice*
Temperature	2.Overtaking	Inflation pressure*	Contaminants
		Load	1.Anti-skid material (salt, sand)
		Temperature	2.Dirt, mud, debris

* Critical factors for pavement friction

Effect of Temperature

As shown in Figure 2.16, researchers (Ahammed and Tighe, 2008b, Jayawickrama and Thomas, 1981) found that PCC wet surface friction varies by up to 10 British Pendulum Number (BPN) for various pavement temperatures. The variation of AC wet surface friction was up to 13 BPN depending of pavement temperatures.

Effect of Surface Water

Acting as a lubricant, water has significant negative impact on the friction between tire and pavement. Surface water can partially prevent the penetration of macrotexture into tire rubber. Sometimes water cannot escape and thus causes the water to be present between vehicle tire and pavement surface when the tire tread and macrotexture are both in poor conditions.

The passage of the tire usually can disperse water away if the water film on the pavement surface is not thick. However, a phenomenon call hydroplaning will happen if

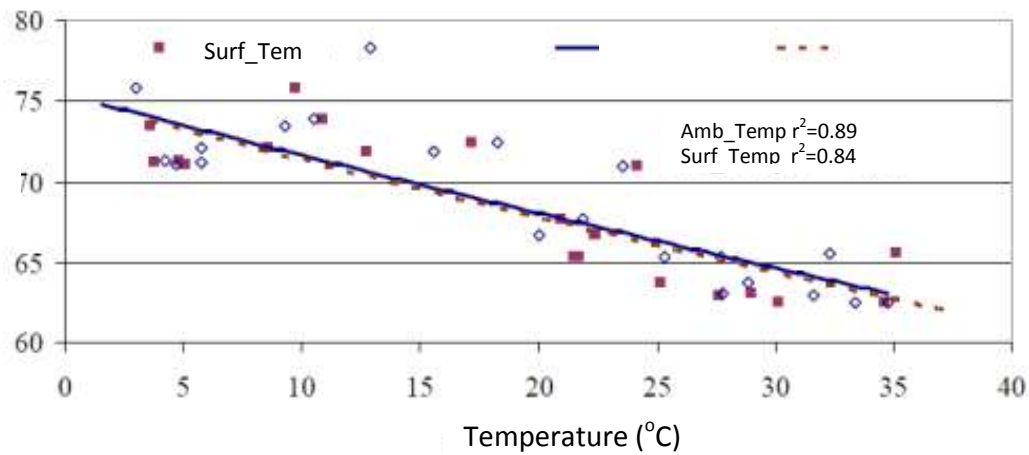


Figure 2.16: Effect of pavement surface and ambient temperatures on monthly friction variation (Ahmed and Tighe, 2008b).

the water film on the road surface is too thick, which will lead to the loss of tire traction. The effect of water film thickness (WFT) on friction is minimal at low speeds ($\leq 32\text{km/h}$) and very significant at higher speeds ($\geq 64\text{km/h}$) (AASHTO, 2008). As shown in Figure 2.17, the coefficient of friction of a vehicle tire sliding over a wet pavement surface decreases exponentially as WFT increases. The decrease rate of coefficient of friction gets slower when WFT increases. In addition, the effect of WFT is affected also by tire design and condition (AASHTO, 2008). Since the tread and grooves are helpful to disperse water away, a new tire is less sensitive to WFT.

Figure 2.18 shows a crash in Winnipeg in 2012. Wet driving condition and hence lower friction might be one of the major contributors to this three vehicle crash from a pavement engineer's point of view.

Effect of Snow and Ice

Snow and ice on the pavement surface present the most hazardous condition for vehicle braking. The friction between the tires and the pavement is so low that almost any sudden braking or change of direction results in locked-wheel sliding. As a result, it

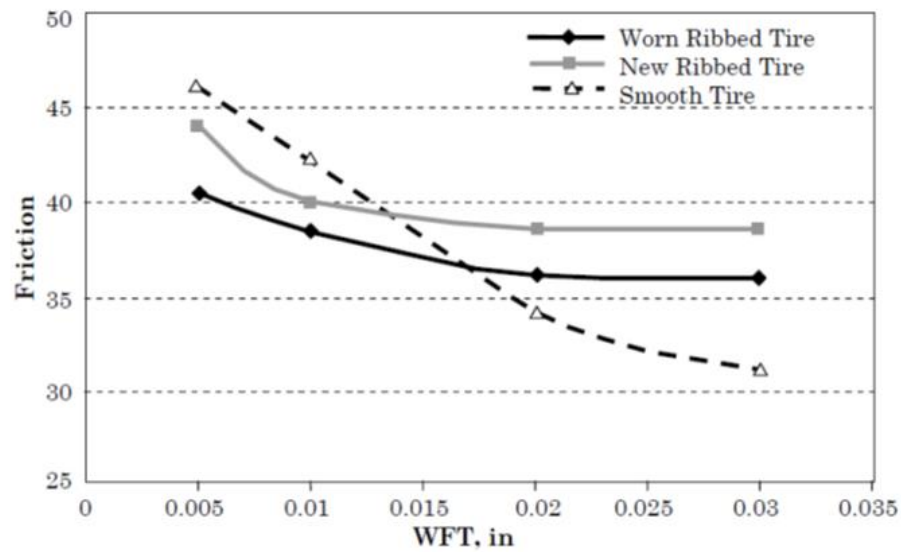


Figure 2.17: Effect of water film thickness on pavement friction (Henry, 2000).



Figure 2.18: Three vehicles crashed on wet pavement (WinnipegFreePress, 2012).

will lose the vehicle directional stability. Al-Qadi *et al.* (2002) found that vehicle friction performance can be dramatically decreased when the tire contact area can not reach the pavement surface due to ice or snow. The presence of ice and snow makes the roadways very slippery, as can be seen from Figure 2.19 , as many as six vehicles were in the ditch in the morning of April 4, 2014 on highway 221 and Sturgeon Road in Winnipeg (Dineen, 2014).



Figure 2.19: Vehicles in ditch due to ice and snow (Dineen, 2014).

Effect of Pavement Distress

Pavement distresses are the results of traffic loading, environmental loading, material and construction quality among other factors. PCC pavement distresses include block cracking, edge cracking, spalling, blowouts, scaling and map cracking. The distresses for AC pavement are: rutting, fatigue cracking, longitudinal cracking, transverse cracking, block cracking, patches, potholes, raveling, and bleeding. Pavement surface ruts, which can be denoted by international roughness index or IRI, have a major impact on roadway friction and safety (Chan et al., 2008).

Pavement roughness may lead to vehicles loss of control when braking or turning. The contact area between vehicle tire and pavement will decrease with the increases of IRI, thus leading to a lower brake friction. Very high IRI of pavement can cause differential friction (the coefficients of friction are different for the tires on either side of the vehicle). A vehicle may skid on pavement because of differential friction . Rutting is “risky especially in wet pavement condition if water accumulates in the rut path which will result in hydroplaning because of the lack of contact between tire and pavement surface texture due to water” (Chan et al., 2008).

Effect of Tire Properties

The type, pattern, and depth of a tire tread are very important for the friction level between vehicle tire and pavement surface. The condition of tire tread is critically important on wet surface by draining water away from the tire to prevent hydroplaning from happening. Researchers (Henry, 2000) found that wet condition friction can be 70% less for completely worn tires than new ones.

The tire rubber property is another important factor for friction especially when temperature is low. If tire rubber is too stiff, the tire cannot deform and the hysteresis component of friction will be very low. The tire footprint will be just a fraction of the area as expected for a flexible tire. Smaller footprint will provide much less traction and friction for a vehicle. This is the reason that it is compulsory to put on winter tires in some jurisdictions (e.g. Quebec).

On extreme conditions, studded tires can be another choice. Researchers (Scheibe, 2002) found that studded winter tires were superior to studless winter tires or all season tires in all conditions including, ice, snow, slush and wet pavement. The use of studded tires is restricted to certain conditions because of the increased cost associated with pavement damage (Tremblay and Fitch, 2011).

2.4 Road Safety

Road safety can be characterized as “a driving environment free from danger or one that is operated with rules and features designed to minimize crashes and the associated consequences” (Hall et al., 2009b).

2.4.1 Road Safety Deserves Attention

The injuries due to traffic collisions in Canada are a major burden on the health care system in terms of emergency treatment, chronic care, and rehabilitation (Ramage, 2008). In 2008, Canada was ranked number 10 in terms of fatalities per billion vehicle kilometres (VKM) traveled compared to other member countries of the Organization for Economic Cooperation and Development, as shown in Table 2.5 (Transport Canada, 2011b).

Table 2.5: Fatalities rate in various countries (Transport Canada, 2011b).

Rank	Country	Fatality rate (Per Billion VKM)
1	Great Britain	4.99
2	Sweden	5.14
3	Netherlands	5.25
4	Ireland	5.66
5	Switzerland	5.99
6	Finland	6.5
7	Germany	6.5
8	Norway	6.65
9	Australia	6.9
10	Canada	7.18
11	France	7.74
12	United Sates	7.91
13	Denmark	8.22

The United Nations’ report entitled World Report on Road Traffic Injury Prevention (Peden et al., 2004) noted that:

- More than one million people are killed every year in road crashes all over the world. Roughly about five million are injured due to these accidents.
- Based on the current conditions, roadway related injuries and fatalities will likely increase dramatically in the next 20 years all over the world, especially in developing countries, if no effective action is taken.
- Traffic related accidents would become the third major cause of death.
- The major victims of these traffic collisions are people between 5 and 44 years old.
- These traffic accidents will cost 2-3% of a country's Gross Domestic Products.

According to Transport Canada (2011a), the number of traffic fatalities and serious injuries occurring in Canada from 1992 to 2011 are shown in Table 2.6.

More than half of fatalities were drivers and about 20% were passengers of vehicles according to the data between 2007 and 2011. The social costs of the motor vehicle collisions per year including the cost of loss of life, medical treatment, rehabilitation, lost productivity, and property damage are in the range of tens of billions of dollars (Transport Canada, 2011a, CCMTA, 2010).

Table 2.7 shows the casualty rates for various Canadian jurisdictions in 2011.

It is reported that a person dies every four hours or is admitted to hospital every 90 minutes as a result of a traffic collision (Transport Canada, 2011a).

2.4.2 Effect of Pavement Friction on Road Safety

Four types of factors affecting road safety are: pavement surface condition, vehicle operational parameters, tire properties, and environmental factors.

It is understandable that most roadway crashes involve multiple causative factors. However, crash investigations have found that pavement surface conditions including tex-

Table 2.6: Collisions and casualties in Canada 1992 to 2011 (Transport Canada, 2011a).

Year	Collisions		Victims		
	Fatal ¹	Personal injury ²	Fatalities ³	Serious injuries ⁴	Injuries ⁵ (total)
1992	3,073	169,640	3,501	25,521	249,823
1993	3,121	168,106	3,615	23,902	247,593
1994	2,837	164,642	3,230	21,564	241,899
1995	2,817	161,950	3,313	20,188	238,458
1996	2,740	153,944	3,129	18,734	227,283
1997	2,660	147,549	3,076	17,294	217,401
1998	2,583	145,615	2,919	16,197	213,319
1999	2,632	148,683	2,980	16,187	218,457
2000	2,547	153,300	2,903	15,581	222,840
2001	2,413	148,996	2,756	15,283	216,463
2002	2,583	153,859	2,921	15,906	222,681
2003	2,487	150,503	2,777	15,120	216,147
2004	2,436	145,161	2,731	15,585	206,125
2005	2,550	145,572	2,898	15,812	204,725
2006	2,587	142,521	2,872	15,882	199,984
2007	2,462	138,612	2,753	14,235	192,744
2008	2,192	127,678	2,436	12,722	176,527
2009	2,011	123,516	2,223	11,831	170,877
2010	2,026	123,141	2,237	11,645	170,629
2011	1,834	121,159	2,006	10,443	166,725

1. "Fatal collisions" include all reported motor vehicle crashes that resulted in at least one death, where death occurred within 30 days of the collision, except in Quebec before 2007 (8 days).
2. "Personal injury collisions" include all reported motor vehicle crashes which resulted in at least a injury but not death within 30 days of the collision, except in Quebec before 2007 (8 days).
3. "Fatalities" include all those who died as a result of a reported traffic collision within 30 days of its occurrence, except in Quebec before 2007 (eight days).
4. "Serious Injuries" include hospitalized persons for treatment or observation. Serious injuries were estimated from 1992 to 2011 because several jurisdictions under-reported these numbers.
5. "Total Injuries" include all reported severities of injuries ranging from minimal to serious.

Table 2.7: Casualty rates of various jurisdictions in Canada (Transport Canada, 2011a).

Jurisdiction	Per 100,000 population		Per billion vehicle-kilometres		Per 100,000 licensed drivers	
	Fatalities	Injuries	Fatalities	Injuries	Fatalities	Injuries
Canada	5.8	483.5	5.8	485.0	8.4	699.6
N.L.	5.5	402.8	5.5	407.5	7.7	567.1
P.E.I.	12.4	465.4	13.4	503.6	17.9	675.7
N.S.	6.7	520.2	6.2	480.1	9.3	716.5
N.B.	8.3	376.3	7.6	344.3	11.4	512.8
QUE.	6.1	519.4	6.6	565.6	9.4	803.6
ONT.	3.5	458.1	3.7	479.8	5.0	653.6
MAN.	8.8	657.3	8.9	662.6	13.5	1,011.1
SASK.	14.2	650.1	11.2	512.6	20.4	934.8
ALTA.	8.3	491.9	5.7	338.7	11.1	657.7
B.C.	6.4	426.3	8.0	536.1	9.2	615.0
Y.T.	25.4	545.2	17.9	383.0	41.8	896.7
N.W.T.	0.0	244.3	0.0	332.5	0.0	437.4
NVT.	8.9	128.2	83.5	1,197.0	49.9	715.1

ture and friction characteristics are significant factors to roadway crashes. It is extremely important to have an in-depth knowledge and understanding of the relationship between crashes and pavement surface characteristics (Hall et al., 2009b).

Tire-pavement friction is one of the important properties of a pavement that affects road safety although it is difficult to quantify how much of the improvement in road safety can be attributed to the improvements of road surface texture.

According to Transport Canada (2011b), 2,766 people died and another 222,455 were injured (17,730 seriously) on Canadian roads in 2003 from a total of 156,904 police reported crashes. Highway crashes costs about \$25 billion annually in Canada. In the United States, 42,643 fatalities and about 2.9 million injuries were reported in 2005 (McKinney and Gibson, 2009). These traffic related incidents significantly affected the US economy with about \$230.6 billion loss as of year 2000 in addition to the pain and suffering of the society (Noyce et al., 2005). Hoerner and Smith (2002) found that skidding contributes to 15% to 35% of wet pavement accidents. It was found that (TRID, 2003) skidding on wet pavements contributes to 13.5% of fatal and up to 25% of all accidents.

Provision of adequate friction on pavement surface is a key objective to minimize the skid related accidents. Studies have found that skid related accidents can be reduced by an improvement in pavement surface friction (Rogers et al., 2003). For example, the wet/dry pavement accident ratio was shown to increase sharply from a ratio of 0.23 to about 0.7 as the skid number, measured at 64 km/h (SN64), drops below 41 which is the critical value of SN64 (Rizenbergs et al., 1976). Other studies found that an improvement of average friction by 0.1 can reduce the wet-accident rate by 13% (Kennedy et al., 1990, Hosking, 1990).

It is reported that 70% of wet pavement crashes can be prevented or minimized by improving pavement friction (Swanlund and Cheung, 2013). Pavement friction plays a vital role in keeping vehicles on the road because it gives drivers the ability to have an appropriate control over their vehicles. Researchers (Rizenbergs et al., 1972, Wallman and Astrom, 2001) have found that the number of wet crashes increases as pavement friction decreases although it is difficult to establish a quantitative relationship between wet-weather crashes and pavement friction.

Research shows that when pavement friction falls below a site-specific threshold value, the risk of wet crashes increases significantly (Kutttesch, 2004). In their study, Viner et al. (2005) found that crash risk approximately halves as pavement friction doubles over normal ranges, as shown in Figure 2.20.

In summary, surface texture is the key feature to affect pavement friction, noise, and safety. There is a need for deep understanding of pavement surface texture by using 3D measurement and analysis of pavement surface texture as specified in Chapter 1.

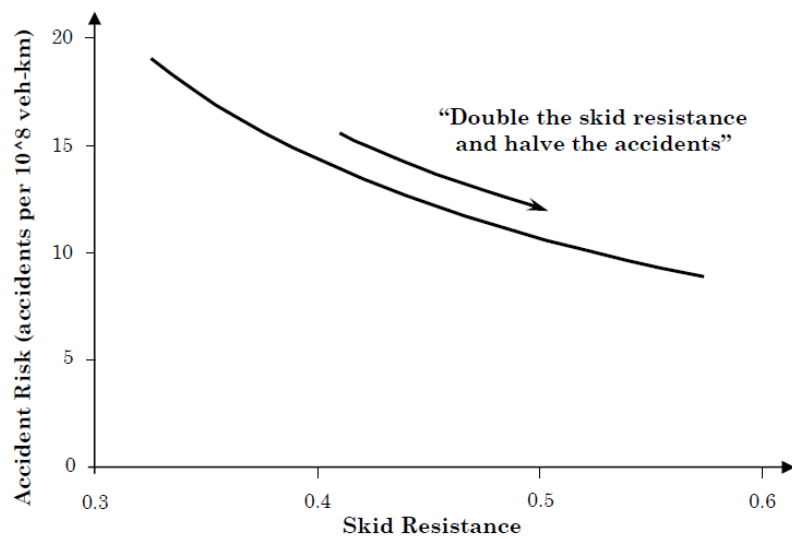


Figure 2.20: Relationship between pavement friction and crash risk (Viner et al., 2005).

Chapter 3

METHODOLOGY

This chapter outlines the methodology used to conduct research including data collection (texture measurement), data processing, proposed 3D texture parameters, and the validation of texture parameters.

This chapter: (1) presents the research methodology of this study, (2) selects pavement scenarios for texture measurement, (3) describes the procedure for data processing, (4) defines new 3D texture parameters, and (5) summarizes the tools and methods to verify the proposed 3D texture parameters in this research.

3.1 Research Methodology

An experimental research methodology is used for field experiments to isolate and control every relevant condition which determines the events investigated, so as to observe the effects when the conditions are manipulated (Clarke, 2005).

Discrete wavelet transform (DWT) methodology is employed to decompose the measured surface topography into various frequency components and then to define microtexture and macrotexture parameters independently. Section 3.2 elaborates the DWT methodology used in this thesis.

A regression research methodology is used to investigate the possible relationships between pavement texture indices and pavement friction/noise that obtained from field experiments.

The research methodology is shown in Figure 3.1

The objectives of this study are:

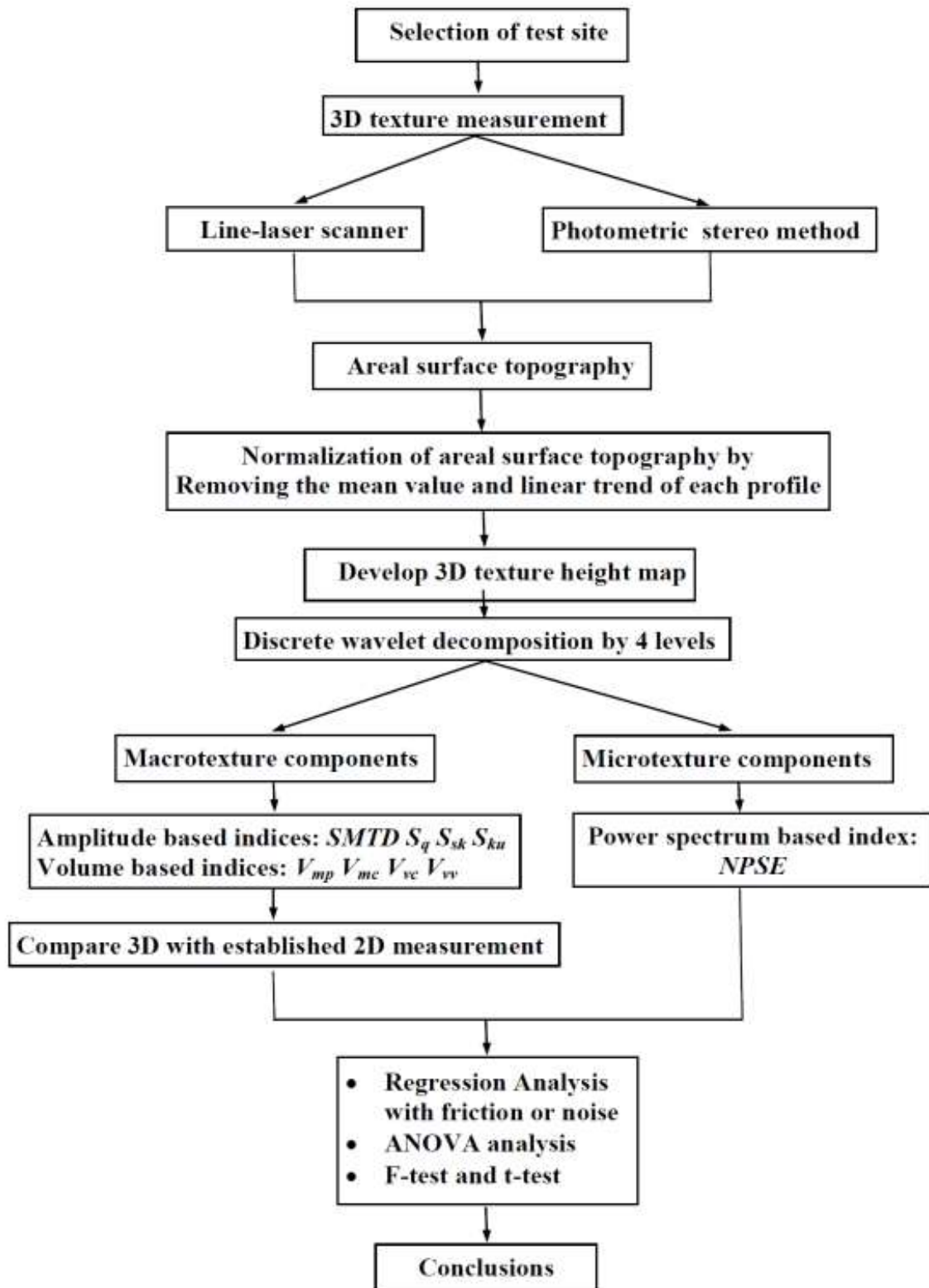


Figure 3.1: Methodology flowchart for 3D texture measurement and analysis.

- To retrieve the pavement texture by using two methods: photometric stereo method and line-laser scanning method.
- To explore a set of three-dimensional (3D) texture indices to address the pavement texture for area-wide texture properties. The current texture standards rely mainly on 2D profile based methods to retrieve texture properties. Two-dimensional texture index, e.g. mean profile depth (MPD), discards potentially useful information about the surface.
- To explore the relationship between pavement friction/noise and the pavement texture indices.

The findings of this research can be used: to specify appropriate pavement texture types, to upgrade specifications of pavement texturing, to find ways to build high frictional pavement, to correlate pavement texture with traffic safety analysis, and to simulate numerically the tire/pavement interaction (Liu and Shalaby, 2013b).

3.2 Wavelet Transform for Analyzing 3D Texture Height Map

3.2.1 Introduction to Space-Frequency Analysis

In signal processing, space (or time)-frequency analysis is to study a signal in both the space (or time) and frequency domains simultaneously. Joseph Fourier (1768 - 1830) introduced, in the early 1800's, Fourier series which provided the foundations for modern signal analysis.

The Fourier transform (FT) decomposes any periodic function, a complex sound, for instance, into a set of orthonormal basis functions of sines and cosines. The coefficients of these orthonormal basis functions represent the contribution of the sine and cosine components of the signal at all frequencies. This allows the signal to be analyzed in terms of

its frequency components. If the analyzed signal consists of N discrete data points, the computation of FT requires N^2 multiple operations which can be very time consuming for large N . Cooley and Tukey (Cooley and Tukey, 1965) proposed an efficient algorithm, fast Fourier transforms (FFT), to compute the discrete Fourier transform and its inverse. The FFT improved the computational efficiency of the Fourier transform of a signal represented by N discrete data points from an order of N^2 to $N \times \log(N)$ arithmetic operations. As a result, fast Fourier transforms are widely used for many applications in engineering, science, and mathematics.

Despite the functionality of the Fourier transform, especially in regard to obtaining the spectral analysis of a signal, there are two major shortcomings of this technique (Altmann, 1996):

- Local features can be lost or misled. FT is unable to accurately represent functions that have non-periodic components that are localized in time or space. This is due to the Fourier transform assumes that the signal to be transformed is periodic in nature and of infinite length.
- FT is unable to provide any information about the time dependence of a signal because FTs are averaged over the entire duration of the signal. This is a problem when analyzing signals of a non-stationary nature. It is often beneficial to acquire a correlation between the space (time) and frequency domains of a non-stationary signal.

Wavelet transform or wavelet analysis (Daubechies, 1988) is an analytical tool developed recently to overcome the shortcomings of the Fourier transform. The wavelet transform can be used to decompose a signal into different frequency components and then present each component with a resolution matched to its scale. Wavelet analysis is capable of revealing aspects of data that FT misses.

Similar to Fourier analysis, Wavelet analysis also breaks a signal down into its constituent parts for analysis. However, the wavelet transform breaks the signal into its “wavelets”, scaled and shifted versions of the “mother wavelet”, instead of a series of sine waves of different frequencies by the Fourier transform. A brief comparison is shown below:

- FT is able to tell what frequencies are present in the signal. A wavelet transform is able to tell what frequencies are present and where (or at what scale). For a signal that was changing in space (or time), the FT is unable to tell where (space) or when (time) this has occurred.
- As shown in Figure 3.2 which is comparing a sine wave (smooth and of infinite length) to the Debauchies 3 wavelet (irregular in shape and compactly supported), Fourier transform is an integral from $space = -infinity$ to $space = +infinity$. So there is no space localization. A wavelet is a wave-like oscillation with an amplitude that starts out at zero, increases, and then decreases back to zero. Thus a wavelet can be defined within a certain space span, starting at $f(space_0) = 0$ and ending at $f(space_{end}) = 0$.

Being irregular in shape and compactly supported feature make wavelet an ideal tool for analyzing signals of a non-stationary nature (e.g. areal surface topography). Their irregular shape lends them to analyzing signals with discontinuity's or sharp changes, while their compactly supported nature enables temporal localization of signals features (Altmann, 1996).

3.2.2 Wavelet Mother Function Used in This Thesis

Alfred Haar, a German mathematician, developed in 1910 the now called Haar function and associated Haar matrix. The matrix is constructed in such a way that all vectors are

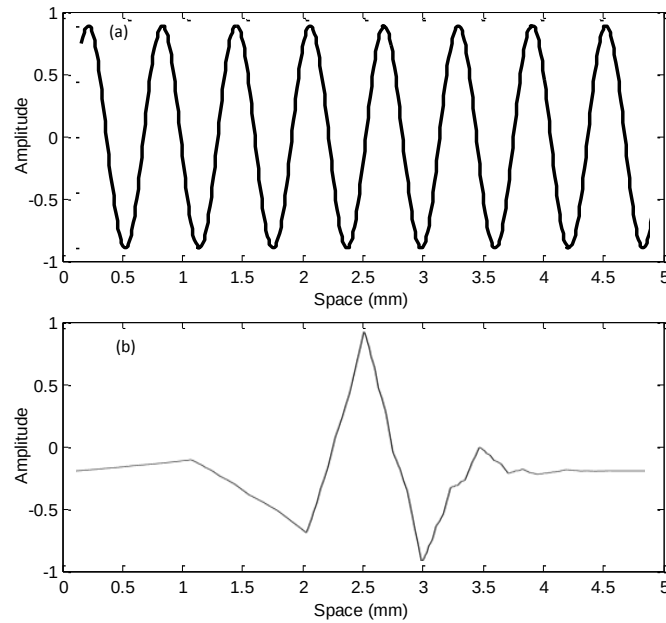


Figure 3.2: Sine wave for FT (a) and $Db3$ -wavelet function Ψ (mother function) for wavelet transform (b) (Altmann, 1996).

perpendicular to each other due to the special ‘mother’ vector. With this scheme it was possible to create orthogonal matrices of any size, all vectors being based on the first vector. This is the first known construction of a wavelet (Bomers, 2000).

In 1980, A. Grossmann and J. Morlet broadly defined wavelets in the context of quantum physics. It was Grossmann and Morlet who first suggested the name wavelets (Jawerth and Sweldens, 1994).

A wavelet is a waveform of effectively limited duration that has an average value of zero. Named after Ingrid Daubechies, the Daubechies wavelets are a family of orthogonal wavelets defining a discrete wavelet transform and characterized by a maximal number of vanishing moments for some given support. With each wavelet type of this class, there is a scaling function or ‘father’ wavelet to generate an orthogonal multiple operations.

The Daubechies family of wavelets are usually named as dbN . The number N in the Daubechies family code is related to the smoothness of the wavelet. Wavelets with rapidly

changing features have small N values (e.g. smaller than 3) and vice versa. Figure 3.2 (b) shows the *db3* function which was adopted in this thesis.

An algorithm of signal and Wavelet transform was presented at the 2013 Airfield and Highway Pavements Conference (Liu and Shalaby, 2013c)

3.2.3 Discrete Wavelet Transform (DWT)

The DWT of a discrete signal $s(x)$ at a position i and level j involves the following coefficients as shown in Equation (3.1):

$$\begin{aligned} C(i, j) &= \sum_{j=1}^N s(x) \Psi_{a,b}(x) \\ \Psi_{a,b}(x) &= 2^{-\frac{j}{2}} \Psi(2^j x - i) \end{aligned} \tag{3.1}$$

Where

$s(x)$ = a discrete signal for WDT,

N = total number of data points,

$\Psi_{a,b}(x)$ = wavelet basis function with scaling parameter a and shifting variable b ,

j = decomposition level.

The Daubechies mother wavelet denoted by *db3* was adopted for this research for its usefulness in data analysis (Zeleele and Papagiannakis, 2009, Liu et al., 2004, Liu and Shalaby, 2013a, Liu et al., 2015b).

The DWT allows exceptional localization in both the space (or time) domain via shifting of the mother wavelet, and in the scale (frequency) domain via scaling (Vidakovic and Mueller, 1991). The shifting and scaling operations, as shown in Figure 3.3, applied to the mother wavelet are performed to calculate the wavelet coefficients. The coefficients represent the correlation between the wavelet and a localized section of the signal (a set of discrete data points). The wavelet coefficients are calculated for each wavelet segment, giving a time-scale function relating the wavelets correlation to the signal (Altmann, 1996).

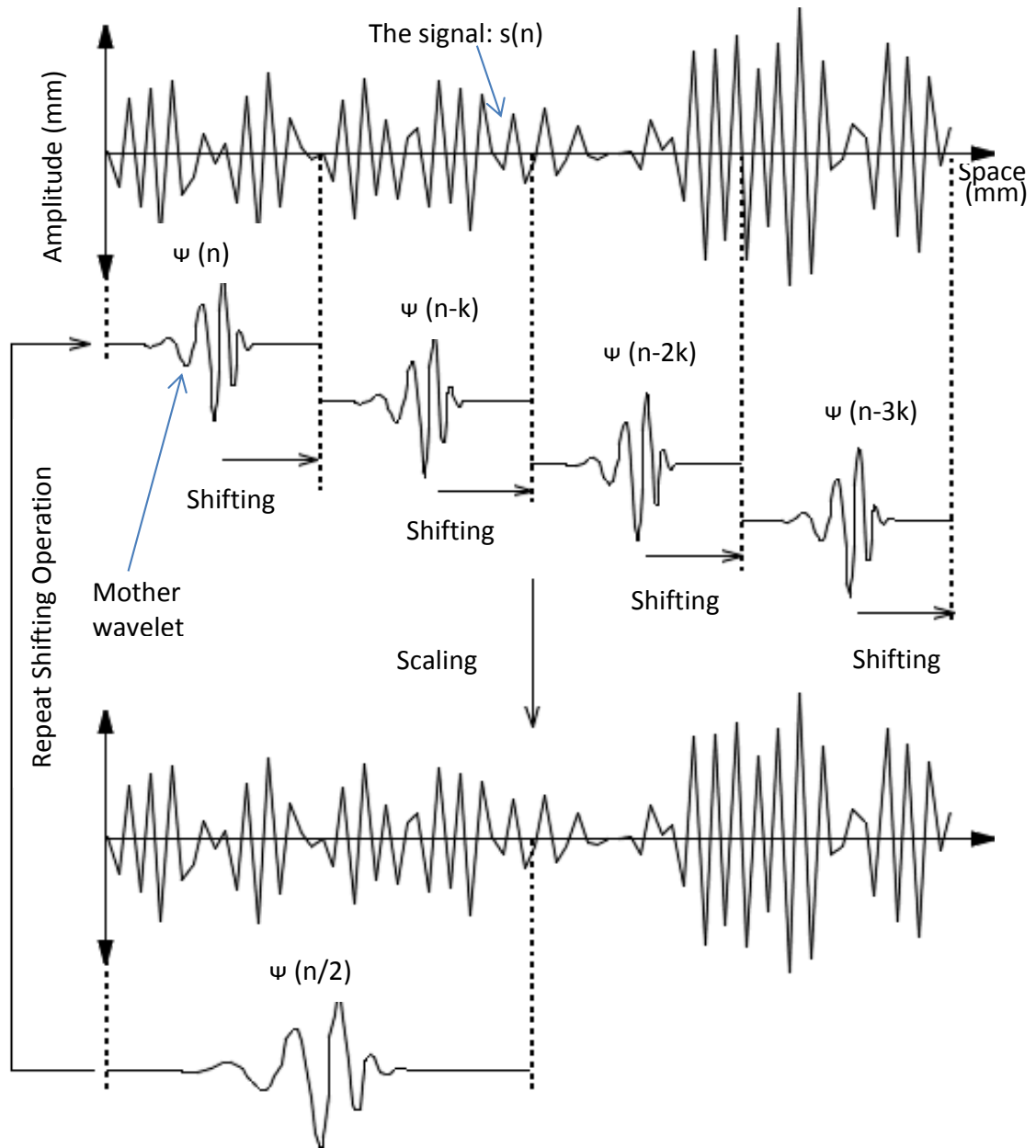


Figure 3.3: The scaling and shifting process of DWT analysis (Altmann, 1996).

For a 2D signal with n discrete data points, $S(n)$, the DWT decomposition process is illustrated as shown in Figure 3.4. As an example, Figure 3.5 shows the approximate coefficients and detailed coefficients of 3 decomposition levels.

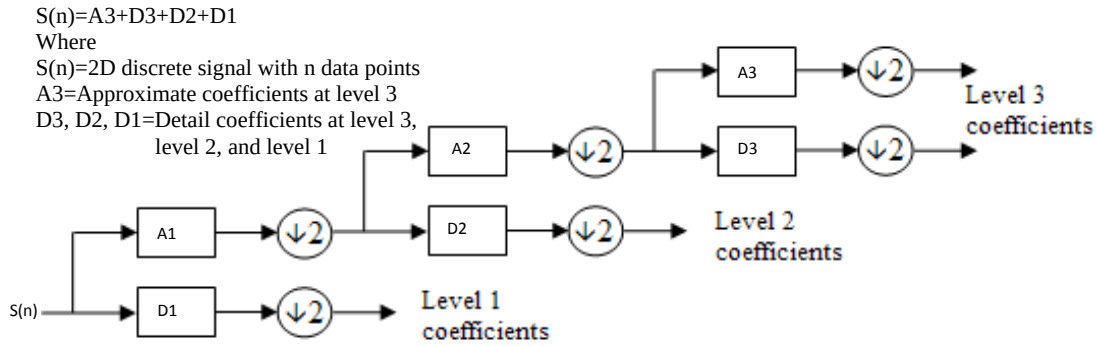


Figure 3.4: 2D discrete signal $S(n)$ decomposition structure (Wikipedia, 2015).

The wavelet decomposition of the 3D signal S has the structure shown in Figure 3.6.

The maximal decomposition level for any signal can be calculated by using Matlab function as shown in Equation (3.2).

$$Maxlevel = wmaxlev(Asize, db3) \quad (3.2)$$

Where

$Maxlevel$ = maximal decomposition level ,

$wmaxlev$ = MATLAB function to calculate $Maxlevel$,

$Asize$ = the size of the 2D signal,

$db3$ = Daubechies mother wavelet.

Pseudo-frequency for various decomposition levels of DWT can be calculated by using Matlab as shown in Equation (3.3).

$$F = scal2frq(2^{l-1}, db3, DELTA) \quad (3.3)$$

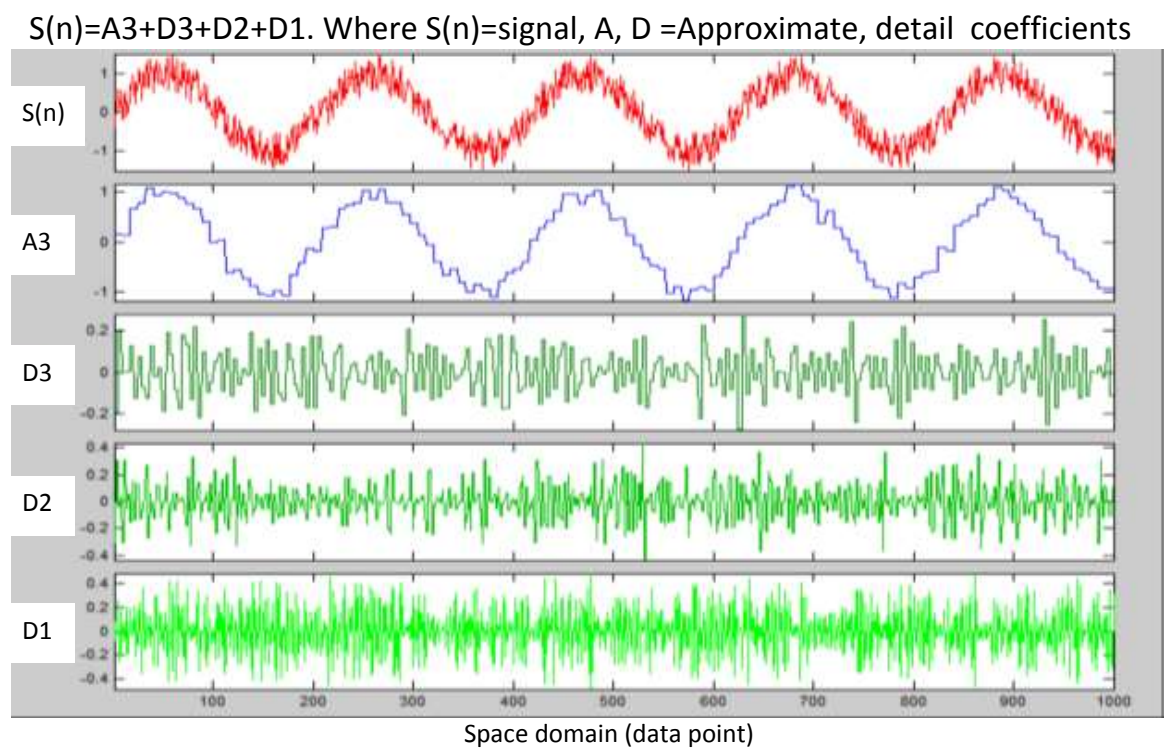
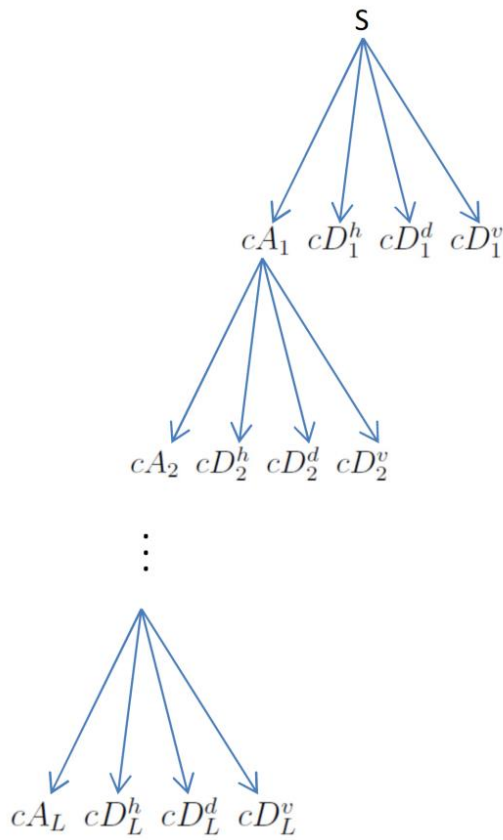


Figure 3.5: 2D discrete signal $S(n)$ decomposition coefficients (Matlab, 2015).



Where

F = pseudo-frequency for various decomposition levels,

$scal2freq$ = MATLAB function to calculate Maxlevel ,

l = the decomposition level,

$db3$ = Daubechies mother wavelet,

$DELTA$ = horizontal resolution in space domain.

3.2.4 Discrete Wavelet Transform for Analyzing 3D Texture Height Map

In this thesis, the measured 3D texture heights were detrended to remove the average elevation and slope for the purpose of normalization. For the normalized 3D texture heights, the average elevation and average slope over the baselength are zero. As an example, Figure 3.7 shows the detrending process of a 2D profile. The detrended texture heights were decomposed into four levels using the DWT to separate microtexture from macrotexture.

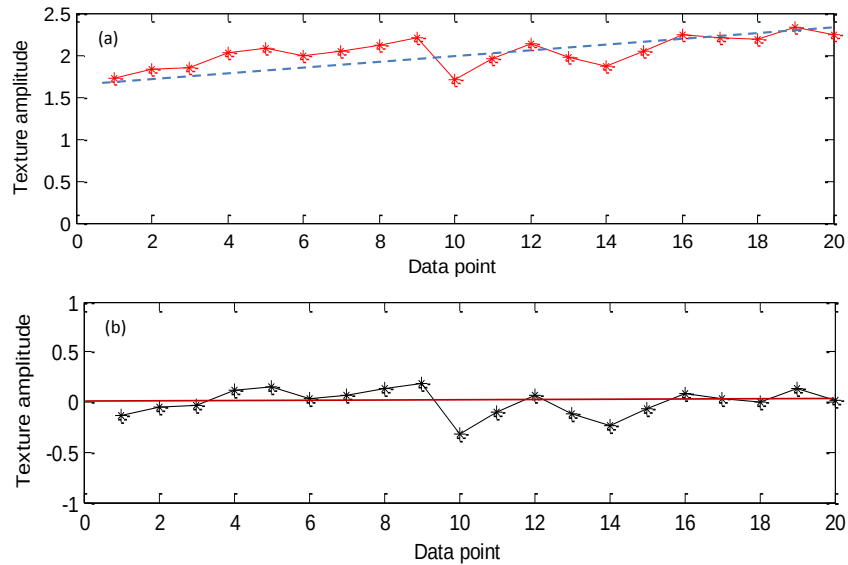


Figure 3.7: Detrending (normalizing) texture profile: (a) original profile with linear trend (straight dashed line) superimposed and (b) detrended profile obtained by subtracting the linear trend from the original profile.

DWT decomposes the texture heights into an approximate component and various levels of detailed components as shown in Equation (3.4).

$$Heights = A_L + \sum_{i=1}^L D_j \quad (3.4)$$

Where

$Heights$ = the recovered pavement surface texture heights,

A_L = approximate component of texture heights (the macrotexture component),

D_j = the detailed component of texture heights at decomposition level of j ,

L = the maximum decomposition level.

The frequency and wavelength band at various decomposition levels are shown in Table 3.1.

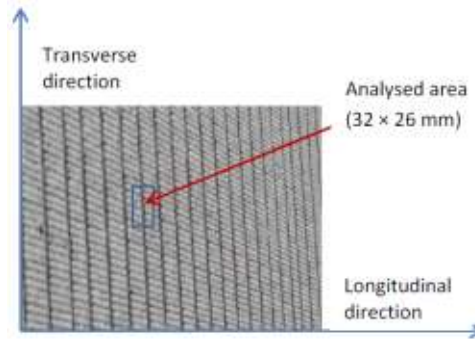
Table 3.1: Frequency and wavelength band for various decomposition levels.

Decomposition level, j	Pseudo-frequency (cycle/mm)	DWT component	Filter	Wavelength (mm)	Texture classification
1	16.4	D1	High pass	0.06 and lower	Microtexture
2	8.2	D2	High pass	0.06-0.12	Microtexture
3	4.1	D3	High pass	0.12-0.24	Microtexture
4	2.0	D4	High pass	0.24-0.49	Microtexture
4	2.0	A4	Low pass	0.49 and higher	Macrotexture

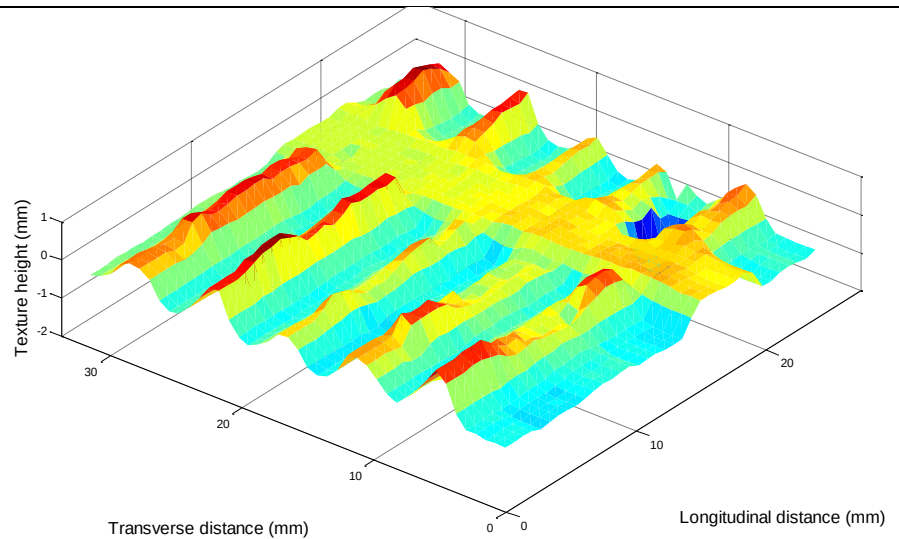
An algorithm of DWT analysis for 3D pavement surface texture map was developed and presented (Liu and Shalaby, 2013c, Liu et al., 2015a, Liu and Shalaby, 2015). As an example, Table 3.2 through Table 3.4 shows a pavement image and its texture height maps at various decomposition levels of DWT analysis. The analyzed area in this example is 32×26 mm instead of 100×100 mm which is the typical dimensions for pavement surface texture measurement. The reason for this adjustment is that the purpose of Table 3.2 through Table 3.4 is to show the various components of the DWT analysis. The visualization is better with fewer data points.

Table 3.2: A pavement image, recovered 3D texture heights, and texture heights of approximate component of DWT analysis.

Pavement image
(PCC pavement
texture: Longitudinal
diamond grind
+transverse diamond
groove)



Recovered pavement
surface texture
heights by using line-
laser scanner with
horizontal resolution
at 0.05 mm



Approximate
component of the
recovered texture
heights at level 4 of
DWT.

The texture
wavelength is
0.49 mm and higher.

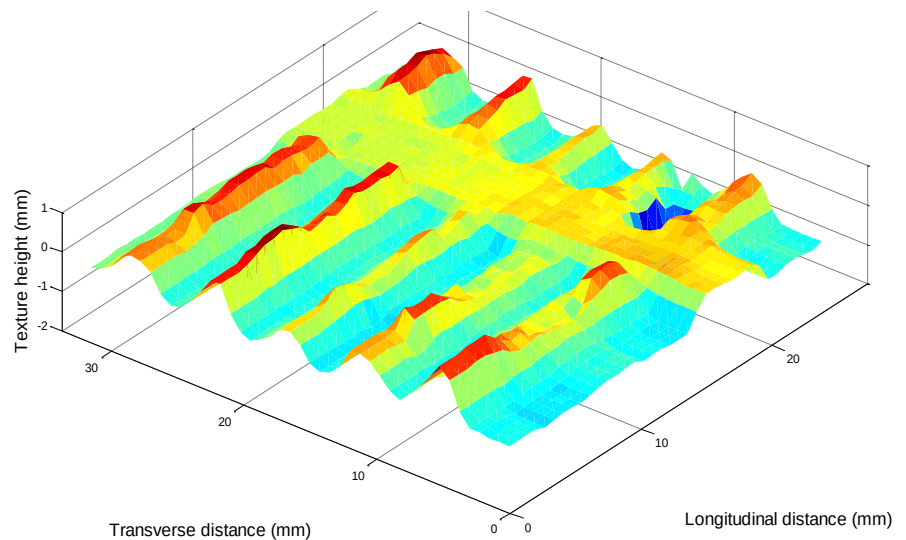
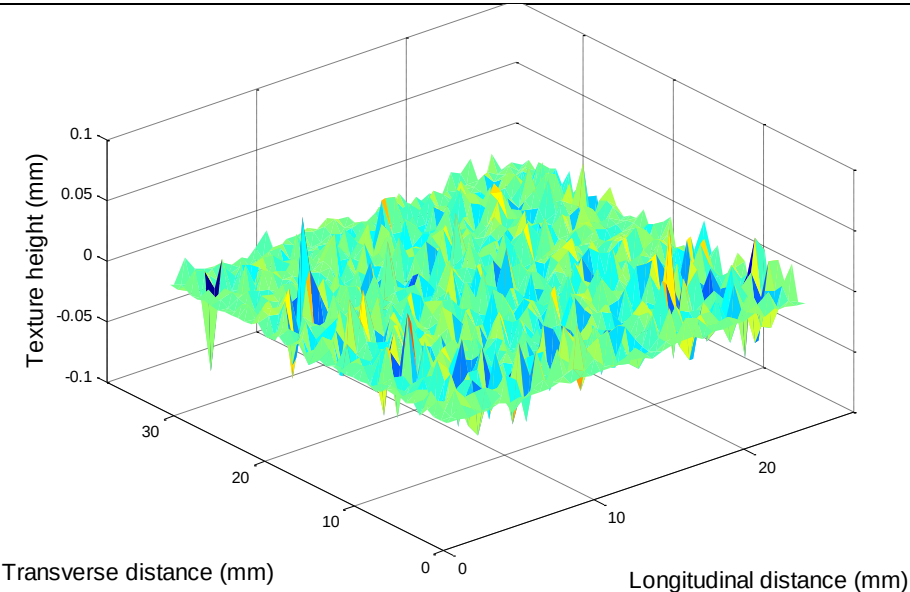


Table 3.3: Texture heights of detailed components at decomposition levels 4 to 2 of DWT analysis (Cont'd from Table 3.2).

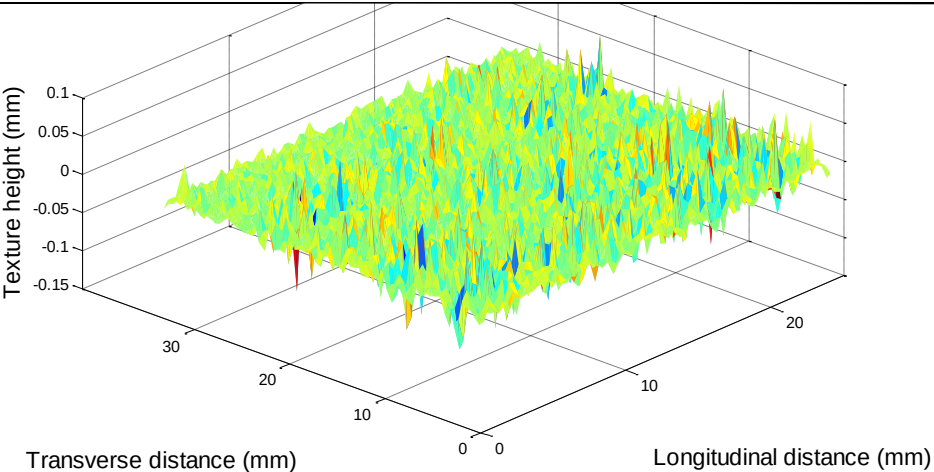
Detailed component
of the recovered
texture heights at
level 4 of DWT.

The texture
wavelength is
0.24 mm -0.49 mm.



Detailed component
of the recovered
texture heights at
level 3 of DWT.

The texture
wavelength is
0.12 mm -0.24 mm.



Detailed component
of the recovered
texture heights at
level 2 of DWT.

The texture
wavelength is
0.06 mm -0.12 mm.

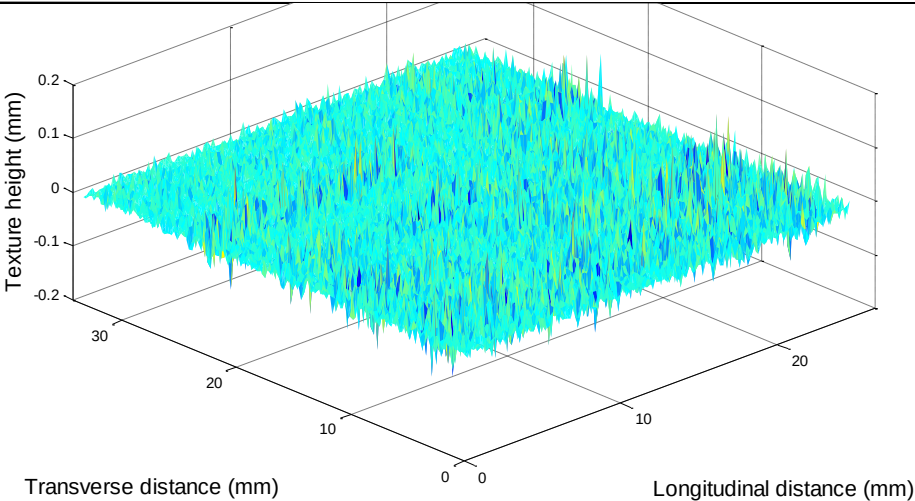
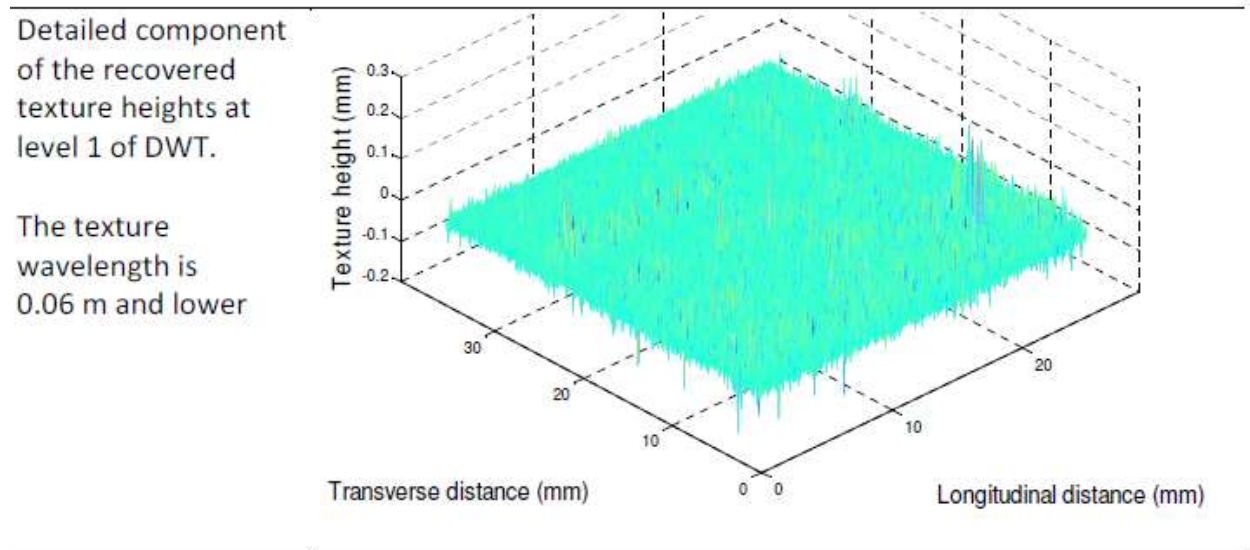


Table 3.4: Texture heights of detailed component at decomposition level 1 of DWT analysis (Cont'd from Table 3.3).



3.3 New 3D Texture Parameters

In current practices, pavement texture indices are based mainly on two-dimensional (2D) texture profile although researchers have been trying to recover the pavement texture in 3D manner in recent years (Rasmussen et al., 2011b). CTM and similar 2D texture measurement devices have the disadvantage of reducing texture data to a single attribute such as mean profile depth (MPD) – which is a 2D estimate of the 3D mean texture depth (Flintsch et al., 2003a).

Three-dimensional texture indices are based on 3D pavement surface texture height maps. As discussed in section 2.1.3, a few sets of 3D texture parameters have been developed in manufacturing industry.

A set of 3D texture parameters were redefined in this research to characterize pavement texture based on the practice of manufacturing and transportation engineering. Since 3D indices are retrieved from a surface texture height map of the pavement instead of a

single profile, the 3D indices will increase the representativeness of the pavement texture. With 3D indices, it is possible to go one step further to calculate volume based functional indices.

The proposed 3D parameters to characterize pavement surface were shown in Table 3.5 followed by detailed interpretation and calculation equations.

Macrotexture Parameters

The following 3D texture indices were defined and calculated for macrotexture. These parameters and their calculation were based on the approximate component of the recovered texture heights at decomposition level 4 of DWT as shown in Table 3.2.

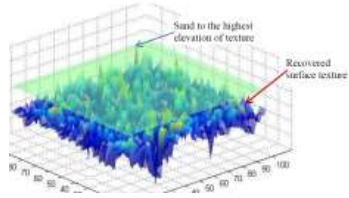
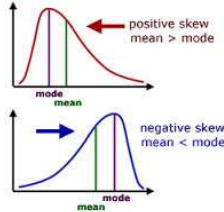
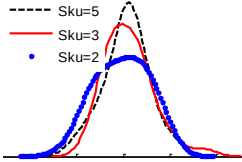
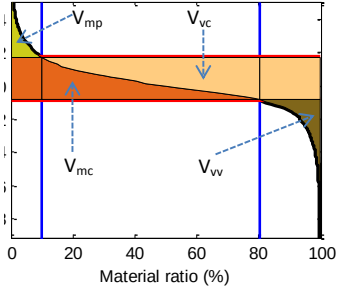
Amplitude Based Indices

One of the objectives of this work is to develop more representative 3D texture indices to replace the current MPD from a single two-dimensional profile and MTD from sand patch method. In this study, texture size and its variation were represented by simulated mean texture depth ($SMTD$) and root mean square deviation (S_q) of the recovered surface texture height map, while texture spacing and shape of distribution were denoted by kurtosis (S_{ku}) and skewness (S_{sk}). The definitions of the 3D macrotexture indicators and their calculations are shown below. These indicators are based on the first, second, third, and fourth moment of the recovered surface texture heights.

1. Simulated mean texture depth ($SMTD$, mm)

Mean texture depth (MTD) is defined and calculated by sand patch method (ASTM E965, 2006). To simulate MTD and sand patch method, $SMTD$ is obtained based on the recovered 3D texture height map with the assumption that the sand will fill in all the hollow space up to the highest elevation of the recovered surface ($100 \times 100mm$)

Table 3.5: The proposed 3D texture parameters.

Texture parameter			Definition	Equation	Schematic
Macro texture	Amplitude based indices	SMTD (mm)	Assuming (simulating sand patch method) sand to fill in all the hollow space up to the highest elevation of the recovered texture surface to calculate the mean texture depth.	Eq. 3.5	
		Sq (mm)	Root mean square deviation, the summation of the standard deviation of the differences between the approximate components of the 3D texture heights and their mean.	Eq. 3.6	
		Ssk (unitless)	Skewness, a measure of the asymmetry of the probability distribution of the approximate components of the 3D texture height map about its mean.	Eq. 3.7	
		Sku (unitless)	Kurtosis, a statistical measure used to describe the distribution of the approximate components of the 3D texture height map around its mean.	Eq. 3.8	
Volume Based indices		Vmp (ml/m ²)	Peak material volume, material volume from the very top surface to 10% material ratio of the bearing area curve and normalized to unity	Eq. 3.9	
		Vmc (ml/m ²)	Core material volume, material volume enclosed from material ratio of 10% to 80% and normalized to unity	Eq. 3.10	
		Vvc (ml/m ²)	Core void volume, void volume enclosed from material ratio of 10% to 80% and normalized to unity	Eq. 3.12	
		Vvv (ml/m ²)	Valley void volume, void volume in the valley zone from material ratio of 80% to 100% and normalized to unity	Eq. 3.11	
Micro texture	Spectrum Based index	NPSE (mm ² /mm ²)	The summation of energy spectral density of the detail components at various frequencies of 3D texture height after DWT analysis. The summation was normalized to unity.	Eq. 3.13	

as shown in Figure 3.8, and that the material volume is calculated using a square-based pyramid for any pixel of the recovered surface. The calculation of SMTD is shown in Equation (3.5).

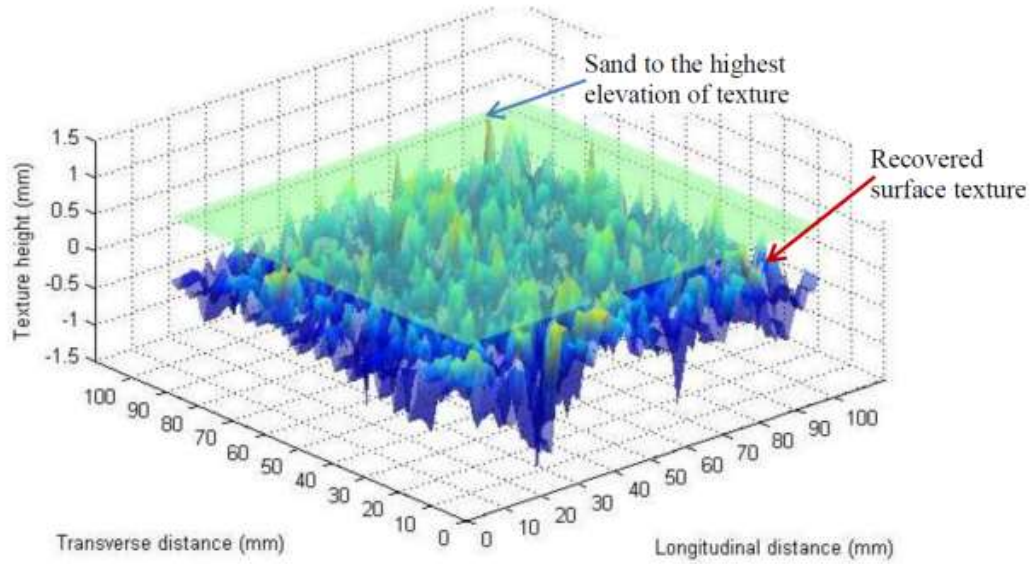


Figure 3.8: Simulation of sand patch method.

$$SMTD = h_{max} - \frac{1}{A} \sum_{i=1}^M \sum_{j=1}^N \frac{1}{3} a h_{ij} \quad (3.5)$$

Where

$SMTD$ = Simulated mean texture depth of the recovered surface texture,

h_{max} = the highest elevation of the recovered surface texture,

h_{ij} = the elevation of any pixel of the recovered texture,

A = the area of the recovered surface,

a = the area of each pixel of the recovered texture,

M, N = number of points in each direction of approximate component of DWT.

2. Root mean square deviation of the recovered surface (S_q, mm)

The root mean square deviation is the standard deviation of the heights of the approximate component of DWT. The S_q is calculated in Equation (3.6).

$$S_q = \sqrt{\frac{1}{A} \sum_{i=1}^M \sum_{j=1}^N ah_{ij}^2} \quad (3.6)$$

Where

S_q =root mean square deviation of the recovered surface texture,

Other variables are as defined previously.

3. *Skewness of the recovered surface (S_{sk} , dimensionless)*

Skewness is a measure of lack of symmetry of a statistical distribution. Recommended by ISO 4287 (1997), skewness can be used to assess the directionality of the surface texture, to differentiate the contribution of positive texture from negative texture. Skewness is calculated in Equation (3.7).

$$S_{sk} = \frac{1}{AS_q^3} \sum_{i=1}^M \sum_{j=1}^N ah_{ij}^3 \quad (3.7)$$

Where

S_{sk} =Skewness of the recovered surface texture,

Other variables are as defined previously.

4. *Kurtosis of the recovered surface (S_{ku} , dimensionless)*

Kurtosis is a measure of whether a set of data are peaked or flat compared to a normal distribution. The S_{ku} for a standard normal distribution is three. If S_{ku} is greater than three, it indicates a peaked distribution, while it means a flat distribution when S_{ku} is smaller than three. S_{ku} is calculated from Equation (3.8).

$$S_{ku} = \frac{1}{AS_q^4} \sum_{i=1}^M \sum_{j=1}^N ah_{ij}^4 \quad (3.8)$$

Where

S_{ku} =Kurtosis of the recovered surface texture,

Other variables are as defined previously.

To facilitate the understanding of skewness and kurtosis, five samples of texture profiles and their S_q , S_{sk} , and S_{ku} are shown in Table 3.6.

Table 3.6: Texture profile samples, skewness, and kurtosis.

Texture profile samples	Root mean square roughness S_q (mm)	Skewness S_{sk}	Kurtosis S_{ku}	Comment
	5	0	3	Gaussian surface
	5	-2	4	Negatively skewed, peaked
	5	2	4	Positively skewed, peaked
	5	0	2	Slowly varying, flat
	5	0	5	Extreme peaked/valley

Volume Based Indices

The parameters are defined with respect to two bearing ratio thresholds of the Bearing Area Curve (BAC) or Abbott-Firestone curve (Whitehouse, 2010) as shown in Figure 3.9. ISO 13565-2 ISO 13565 (1996b) describes a process of transforming a 2D texture profile into a profile-bearing ratio curve by converting the texture profile to a profile-bearing ratio (a type of cumulative distribution of texture elevations). The process begins with the recognition of three distinct regions of texture.

- The peak region is the first to be contacted by a tire, and the most rapid to wear.
- The second region is the core region where most of the texture typically lies, and therefore describes the longevity of the texture.
- The lowest region is the valley region where air and water can reside.

The Abbott-Firestone curve and its three regions will be different for different texture profile or texture heights. By default, the two thresholds are 10% and 80%. Two material volume and two void volume parameters are defined:

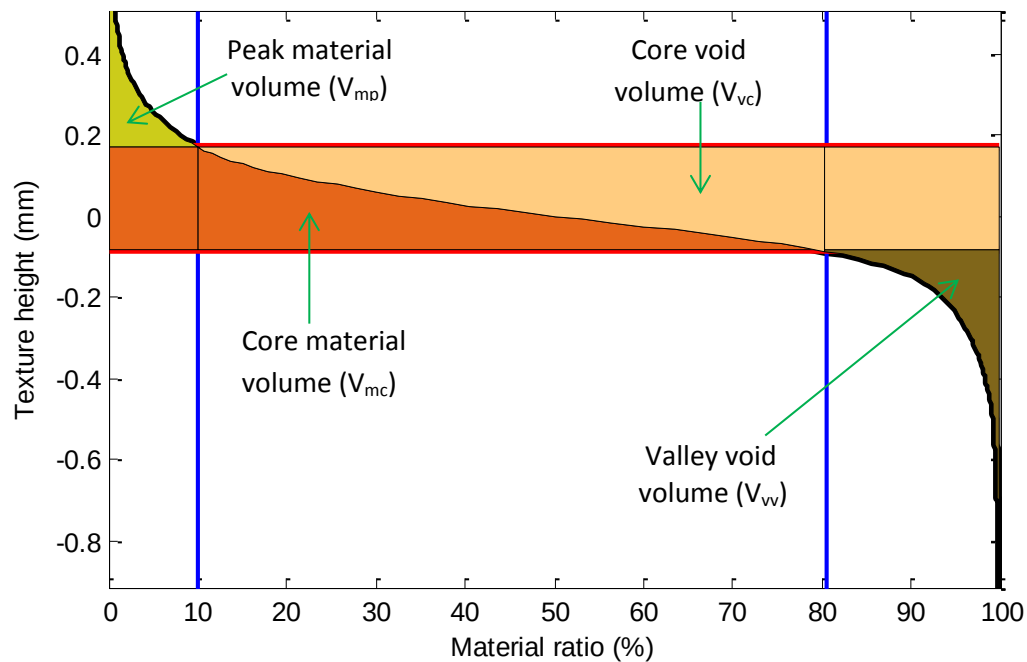


Figure 3.9: Material bearing area curve for pavement texture .

1. *Peak material volume (V_{mp} , ml/m^2)*

V_{mp} is the material volume from the very top surface to 10% material ratio of the BAC and normalized to unity. V_{mp} is calculated from Equation (3.9) (Blunt and Jiang, 2003).

$$V_{mp} = \frac{V_m(h_{0.10})}{A} \quad (3.9)$$

$$\begin{aligned} V_m(h_{0.10}) = & \frac{a}{9} \left\{ 16 \sum_{i=1}^{\frac{M}{2}-1} \sum_{j=1}^{\frac{N}{2}-1} h_{(2i,2j)} + 8 \left[\sum_{i=2}^{\frac{M}{2}-1} \sum_{j=1}^{\frac{N}{2}-1} h_{(2i-1,2j)} + \sum_{i=1}^{\frac{M}{2}-1} \sum_{j=2}^{\frac{N}{2}-1} h_{(2i,2j-1)} \right] \right. \\ & + 4 \left[\sum_{i=2}^{\frac{M}{2}-1} \sum_{j=2}^{\frac{N}{2}-1} h_{(2i-1,2j-1)} + \sum_{i=1}^{\frac{M}{2}-1} [h_{(2i,1)} + h_{(2i,N-1)}] + \sum_{j=1}^{\frac{N}{2}-1} [h_{(1,2j)} + h_{(M-1,2j)}] \right] \\ & + 2 \left[\sum_{i=2}^{\frac{M}{2}-1} [h_{(2i-1,1)} + h_{(2i-1,N-1)}] + \sum_{j=2}^{\frac{N}{2}-1} [h_{(1,2j-1)} + h_{(M-1,2j-1)}] \right] \\ & \left. + [h_{(1,1)} + h_{(1,N-1)} + h_{(M-1,1)} + h_{(M-1,N-1)}] \right\}, \text{ for any } h_{(i,j)} \geq h_{0.10} \end{aligned}$$

Where

V_{mp} = peak material volume,

$h_{0.10}$ = texture height corresponding to material ratio of 10%,

Other variables are as defined previously.

2. Core material volume (V_{mc} , ml/m²)

V_{mc} is the material volume enclosed from material ratio of 10% to 80% and normalized to unity. V_{mc} is calculated from Equation (3.10).

$$V_{mc} = \frac{V_m(h_{0.80}) - V_m(h_{0.10})}{A} \quad (3.10)$$

$$\begin{aligned} V_m(h_{0.80}) = & \frac{a}{9} \left\{ 16 \sum_{i=1}^{\frac{M}{2}-1} \sum_{j=1}^{\frac{N}{2}-1} h_{(2i,2j)} + 8 \left[\sum_{i=2}^{\frac{M}{2}-1} \sum_{j=1}^{\frac{N}{2}-1} h_{(2i-1,2j)} + \sum_{i=1}^{\frac{M}{2}-1} \sum_{j=2}^{\frac{N}{2}-1} h_{(2i,2j-1)} \right] \right. \\ & + 4 \left[\sum_{i=2}^{\frac{M}{2}-1} \sum_{j=2}^{\frac{N}{2}-1} h_{(2i-1,2j-1)} + \sum_{i=1}^{\frac{M}{2}-1} [h_{(2i,1)} + h_{(2i,N-1)}] + \sum_{j=1}^{\frac{N}{2}-1} [h_{(1,2j)} + h_{(M-1,2j)}] \right] \\ & + 2 \left[\sum_{i=2}^{\frac{M}{2}-1} [h_{(2i-1,1)} + h_{(2i-1,N-1)}] + \sum_{j=2}^{\frac{N}{2}-1} [h_{(1,2j-1)} + h_{(M-1,2j-1)}] \right] \\ & \left. + [h_{(1,1)} + h_{(1,N-1)} + h_{(M-1,1)} + h_{(M-1,N-1)}] \right\}, \text{ for any } h_{(i,j)} \geq h_{0.80} \end{aligned}$$

Where

V_{mc} = core material volume,

$h_{0.80}$ =texture height corresponding to material ratio of 80%,

Other variables are as defined previously.

3. Valley void volume ($V_{vv}, ml/m^2$)

V_{vv} is the void volume in the valley zone from material ratio of 80% to 100% and normalized to unity. V_{vv} is calculated from Equation (3.11).

$$V_{vv} = \frac{V_v(h_{0.80})}{A} \quad (3.11)$$

$$\begin{aligned} V_v(h_{0.80}) = & \frac{a}{9} \left\{ 16 \sum_{i=1}^{\frac{M}{2}-1} \sum_{j=1}^{\frac{N}{2}-1} (h_{0.80} - h_{(2i,2j)}) \right. \\ & + 8 \left[\sum_{i=2}^{\frac{M}{2}-1} \sum_{j=1}^{\frac{N}{2}-1} (h_{0.80} - h_{(2i-1,2j)}) + \sum_{i=1}^{\frac{M}{2}-1} \sum_{j=2}^{\frac{N}{2}-1} (h_{0.80} - h_{(2i,2j-1)}) \right] \\ & + 4 \left[\sum_{i=2}^{\frac{M}{2}-1} \sum_{j=2}^{\frac{N}{2}-1} (h_{0.80} - h_{(2i-1,2j-1)}) + \sum_{i=1}^{\frac{M}{2}-1} [(h_{0.80} - h_{(2i,1)} + h_{(2i,N-1)})] \right. \\ & \left. + \sum_{j=1}^{\frac{N}{2}-1} [(h_{0.80} - h_{(1,2j)} + h_{(M-1,2j)})] \right] \\ & + 2 \left[\sum_{i=2}^{\frac{M}{2}-1} [(h_{0.80} - h_{(2i-1,1)} - h_{(2i-1,N-1)})] + \sum_{j=2}^{\frac{N}{2}-1} [(h_{0.80} - h_{(1,2j-1)} - h_{(M-1,2j-1)})] \right] \\ & \left. + [(h_{0.80} - (h_{(1,1)} + h_{(1,N-1)} + h_{(M-1,1)} + h_{(M-1,N-1)}))] \right\}, \text{ for any } h_{(i,j)} \leq h_{0.80} \end{aligned}$$

Where

V_{vv} =valley void volume,

Other variables are as defined previously.

4. Core void volume ($V_{vc}, ml/m^2$)

V_{vc} is the void volume enclosed from material ratio of 10% to 80% and normalized to unity.

V_{vc} is calculated from Equation (3.12).

$$V_{vc} = \frac{V_v(h_{0.10}) - V_v(h_{0.80})}{A} \quad (3.12)$$

$$\begin{aligned}
V_v(h_{0.10}) = \frac{a}{9} & \left\{ 16 \sum_{i=1}^{\frac{M}{2}-1} \sum_{j=1}^{\frac{N}{2}-1} (h_{0.10} - h_{(2i,2j)}) \right. \\
& + 8 \left[\sum_{i=2}^{\frac{M}{2}-1} \sum_{j=1}^{\frac{N}{2}-1} (h_{0.10} - h_{(2i-1,2j)}) + \sum_{i=1}^{\frac{M}{2}-1} \sum_{j=2}^{\frac{N}{2}-1} (h_{0.10} - h_{(2i,2j-1)}) \right] \\
& + 4 \left[\sum_{i=2}^{\frac{M}{2}-1} \sum_{j=2}^{\frac{N}{2}-1} (h_{0.10} - h_{(2i-1,2j-1)}) + \sum_{i=1}^{\frac{M}{2}-1} [(h_{0.10} - h_{(2i,1)} + h_{(2i,N-1)})] \right. \\
& \left. + \sum_{j=1}^{\frac{N}{2}-1} [(h_{0.10} - h_{(1,2j)} + h_{(M-1,2j)})] \right] \\
& + 2 \left[\sum_{i=2}^{\frac{M}{2}-1} [(h_{0.10} - h_{(2i-1,1)} - h_{(2i-1,N-1)})] + \sum_{j=2}^{\frac{N}{2}-1} [(h_{0.10} - h_{(1,2j-1)} - h_{(M-1,2j-1)})] \right] \\
& \left. + [(h_{0.10} - (h_{(1,1)} + h_{(1,N-1)} + h_{(M-1,1)} + h_{(M-1,N-1)}))] \right\}, \text{ for any } h_{(i,j)} \leq h_{0.10}
\end{aligned}$$

Where

V_{vc} = core void volume,

Other variables are as defined previously.

Microtexture Parameter

Normalized power spectra energy ($NPSE, mm^2/mm^2$) was proposed and calculated for microtexture. $NPSE$ is calculated from Equation (3.13). $NPSE$ and its calculation were based on the detailed components of the recovered texture heights from decomposition level 4 to level 1 of DWT as shown in Table 3.3 and Table 3.4.

$$\begin{aligned}
NPSE &= \sum_{i=1}^L NE_j \\
NE_j &= \frac{1}{A} \sum_{i=1}^{M_j} \sum_{k=1}^{N_j} \left[\frac{cD_j^d}{2^j} \right]_{ik}^2
\end{aligned} \tag{3.13}$$

Where

$NPSE$ = normalized power spectra energy,

NE_j = normalized energy for decomposition level j of DWT,

cD_j^d = the diagonal detail coefficients at decomposition level j of DWT,

M_j, N_j = Number of data points of microtexture at decomposition level j ,

L = the maximum decomposition level of DWT.

3.4 Field Tests

To verify the proposed new 3D texture indices, pavement surface texture measurements were made on both Portland cement concrete (PCC) and asphalt concrete (AC) pavements at various locations with numerous types of surface texture. The test sites, devices, texture information, and objectives are shown in Table 3.7.

- Texture test at interstate highway

The South Extension of the I-355 North-South Tollway between I-55 and I-80 near Joliet, Illinois. Thirteen types of PCC surface texture were measured by using photometric stereo device. The objectives of this test are to measure and recover various pavement texture by using photometric stereo method, to compare 3D with 2D texture parameters, and to explore low cost tools to evaluate the impacts of various types of texture.

- Texture test at MnROAD test facilities

Simultaneous line-laser scanner and circular track meter (CTM) testing were conducted on six pavement cells at the MnROAD (Minnesota Department of Transportation, USA) test facilities to compare 3D and 2D texture measurements. Surface texture was measured on six pavement cells from the MnROAD Mainline and Low Volume Road segments. The objective of this test is to compare the proposed 3D

Table 3.7: Test sites for texture measurement.

Classification	Location	Pavement type	Test devices	Objectives
Interstate highway	I-355 North-South Tollway between I-55 and I-80 near Joliet, Illinois. It was for testing Portland cement concrete (PCC) surface texture. Special attention was paid to the design and construction process.	PCC pavement sections with 13 types of textures including both longitudinal and transverse texturing.	1. Photometric stereo device for 3D texture measurement, resolution 0.33mm/point. 2.* Circular track meter (CTM) for 2D texture profiles following ASTM E 2157 standard 3.* Dynamic Friction Tester for friction measurement following ASTM E 1911. 4.* Onboard sound intensity test following TP076-08.	1. Focus on macrotexture only. 2. Verify 3D macrotexture indices by comparing with established 2D indices. 3. Explore relationship between 3D texture parameters and pavement friction or noise.
MnROAD test facilities	Albertville, Minnesota, USA. It is one of the most sophisticated, independently operated pavement test facilities of its type in the world.	Asphalt concrete (AC) pavement and PCC pavement with various texture types	1. Line-laser scanner with horizontal resolution of 0.05 mm and vertical accuracy better than 0.1 mm. 2.* CTM test following ASTM E 2157 standard. 3. Simultaneous line-laser scanner and CTM testing were conducted on six pavement cells at the MnROAD test facilities. Six measurements each cell.	1. Separate macrotexture from microtexture by using discrete wavelet transform for line-laser scanner measurements. 2. Verify 3D macrotexture parameters from line-laser scanner with 2D texture indices from CTM.
Airport runway	Runway 13-31 of the James Armstrong Richardson International Airport (Winnipeg)	Two to ten years old AC pavements PCC pavement with various texture types	1. Line-laser scanner. 2.* Federal Aviation Administration /Transport Canada approved SARSYS Surface Friction Tester	1. Characterize runway surface texture using 3D texture indices. 2. Explore the relationship between 3D texture indices and runway friction.
Municipal roads	1. Manitoba provincial truck highway 8 2. Ryerson Avenue (a local street) in Winnipeg	Conventional hot mixed asphalt contains various percentages of reclaimed asphalt pavement (RAP) or recycled asphalt shingles (RAS)	Line-laser scanner	Assess the impact of various percentages of RAP/RAS on pavement surface texture under various environmental or traffic loading conditions for green pavement solution.

Note: *-- tests were conducted by others.

texture parameters with MPD from the established 2D texture measuring method, the CTM.

- Texture test at airport runway

Texture was measured at runway 13-31 of James Armstrong Richardson International Airport (Winnipeg) by using line-laser scanner for AC pavement and PCC pavement with various texture types. The objectives of this test are: to measure and recover various pavement texture by using line-laser scanner, and to explore relationship between pavement surface texture and pavement friction.

- Texture test at municipal roads

Texture measurements were conducted at provincial truck highway (PTH) 8 between Gimli and Hnaua in Manitoba, Canada. The measured pavements were built with conventional hot mixed asphalt (HMA) and various percentage of reclaimed asphalt pavement (RAP). The objective of this test is to evaluate the impacts of RAP on pavement surface texture. Texture was also measured at Ryerson Avenue Winnipeg. Pavement sections with RAP content of 10% and recycled asphalt shingles (RAS) of 0% or 3%. These pavement sections have been in service for two years at the time of testing. The objective of this test is to evaluate the impacts of RAS on pavement surface texture.

3.5 Summary

Current pavement surface texture measurement and studies focus mainly on macrotexture. There is no established method to measure microtexture directly from image analysis. Pavement surface texture has been measured by using 2D profile based methods. As a result, the texture parameters are 2D based indicators. Two-dimensional macrotexture measurement and texture indicators are insufficient to represent texture for the purpose of

assessing friction and noise. Both microtexture and macrotexture measurements are needed for adequate understanding of friction and noise.

There is a need to measure and recover pavement surface texture in a 3D manner, to develop more representative 3D texture parameters for characterizing pavement texture, and to explore relationship between texture parameters and pavement friction or noise.

The objectives of this research are to measure and recover pavement texture both macro-and microtexture in 3D feature by using either photometric stereo method or line-laser scanner, to propose a set of 3D texture parameters to replace the less informational 2D texture indicators, and to explore relationship between texture parameters and friction and noise of the pavement.

The research methodology and steps of this study are summarized as follows:

- Experimental research methodology is adopted for field tests.
- Correlation research methodology is used to investigate the relationship between texture and pavement friction/noise.
- Measure and recover pavement texture in 3D feature using either photometric stereo method or line-laser scanner.
- The recovered 3D texture height map is detrended to remove the average elevation and slope, if any.
- The detrended 3D texture height map is decomposed into four levels to define its microtexture and macrotexture by using discrete wavelet transform (DWT).
- Texture parameters for macrotexture and microtexture, as shown in Table 3.5, are calculated independently from various components of DWT analysis.

- Regression analysis between texture indices (including both microtexture and macrotexture) and pavement friction and noise is carried out for various tests of this research.
- F-test, t-test, or the analysis of variance (ANOVA) is conducted if necessary to test the significance of the analysis.
- The proposed 3D texture parameters and correlation analysis in this study provide texture indices and low cost tools to evaluate pavement noise and friction.
- It is possible to have a better understanding of texture characteristics and pavement noise/friction by using the combination of 3D parameters proposed in this research.

Chapter 4

PAVEMENT FRICTION/NOISE AND 3D TEXTURE PARAMETERS USING PHOTOMETRIC STEREO METHOD

4.1 Texture Measurement Using Photometric Stereo Method

A photometric stereo device for measuring 3D texture heights of pavement surface has been developed by the Pavement Research Group at the University of Manitoba. This device was successfully used to analyze pavement texture in this research and other studies (El Gendy and Shalaby, 2007, Shalaby and El Gendy, 2012, Liu and Shalaby, 2013c).

A portable photometric stereo device ($40 \times 40 \times 40$ cm) as shown in Figure 4.1 (a), was used to take images for the test pavement. For each texture type, six replicate spots were measured with 4 images for each spot. The azimuth angles for the 4 images were 0° , 90° , 180° , and 270° . A scale template was put onto the top of targeted surface before taking images of the pavement. By using the scale template, the pavement surface area of 100×100 mm close to the centre of each image was used for texture analysis. The analyzed 100×100 mm area consisted of 300×300 pixels at a horizontal resolution 0.33 mm per pixel.

A photometric stereo algorithm (McGunnigle, 1998) was used to compute the gradient of the surface in two perpendicular directions. Local integration technique (Coleman and Jain, 1982) was adopted for recovering the texture heights from surface gradients. Figure 4.1 (b) and (c) show a pavement image and its recovered 3D texture heights.

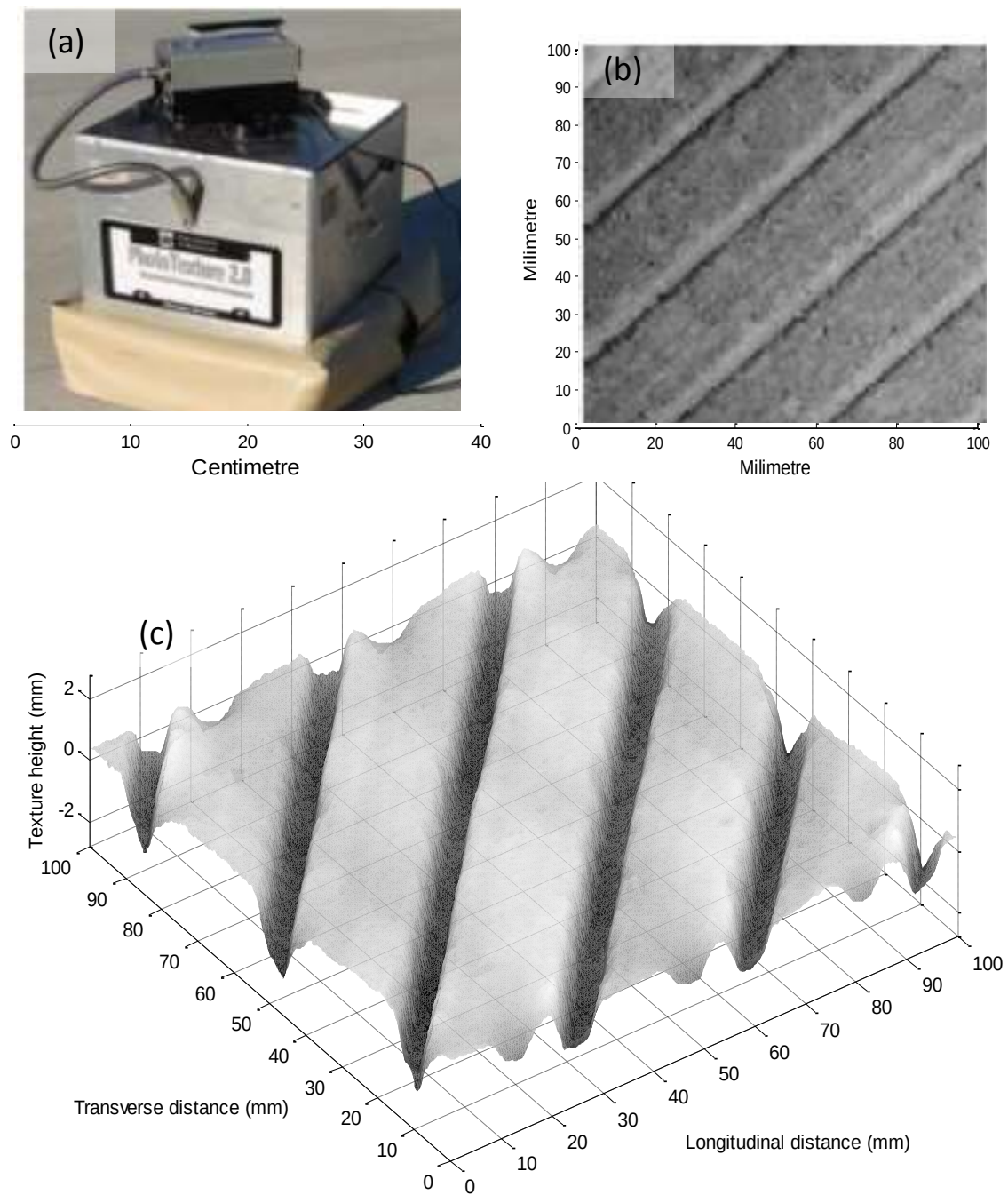


Figure 4.1: A photometric stereo texture measurement device (a) pavement image (b) and recovered texture heights (c).

4.2 Texture Types of the Tested Pavement

As shown in Figure 4.2, the test site is a section of the south extension of the I-355 North-South Tollway between I-55 and I-80 near Joliet, Illinois. This section was selected for constructing and testing Portland cement concrete (PCC) surface texture. Special attention went into the design and construction process. The PCC surface was manually floated and edged prior to the prescribed texturing and curing application. Paving and fresh concrete texturing activities were closely monitored and documented. Tire tread depth gauge measurements of the various tinings were taken to check accuracy of groove dimensions. Locations of the segments were chosen to provide a good representation of the specified texture and to keep clear of roadway features that could affect friction, texture, and noise measurement. Most test segments were about 160 m long. Each segment represents a different type of PCC pavement texture. The texture types and numbering are shown in Table 4.1. These types of texture were found to have good potential to provide adequate friction and reduced noise characteristics (Hall et al., 2009b). Detailed information about the test site can be found at NCHRP report 634 (Hall et al., 2009a). In addition to the photometric stereo method used by the University of Manitoba, texture was also measured by others using Circular Track Meter (CTM) (ASTM E2157, 2009), the Dynamic Friction Tester (DFT) (ASTM E1911, 2009), and high-speed texture profiler (International Cybernetics Corporation Model MDR 4081-T 64-Hz laser texture system). Pavement friction was measured by others using DFT. Sound intensity (SI) noise was measured by others in accordance with AASHTO Provisional Standard TP076-08 (AASHTO-TP076-08, 2008). Field data is shown in Table 4.2.

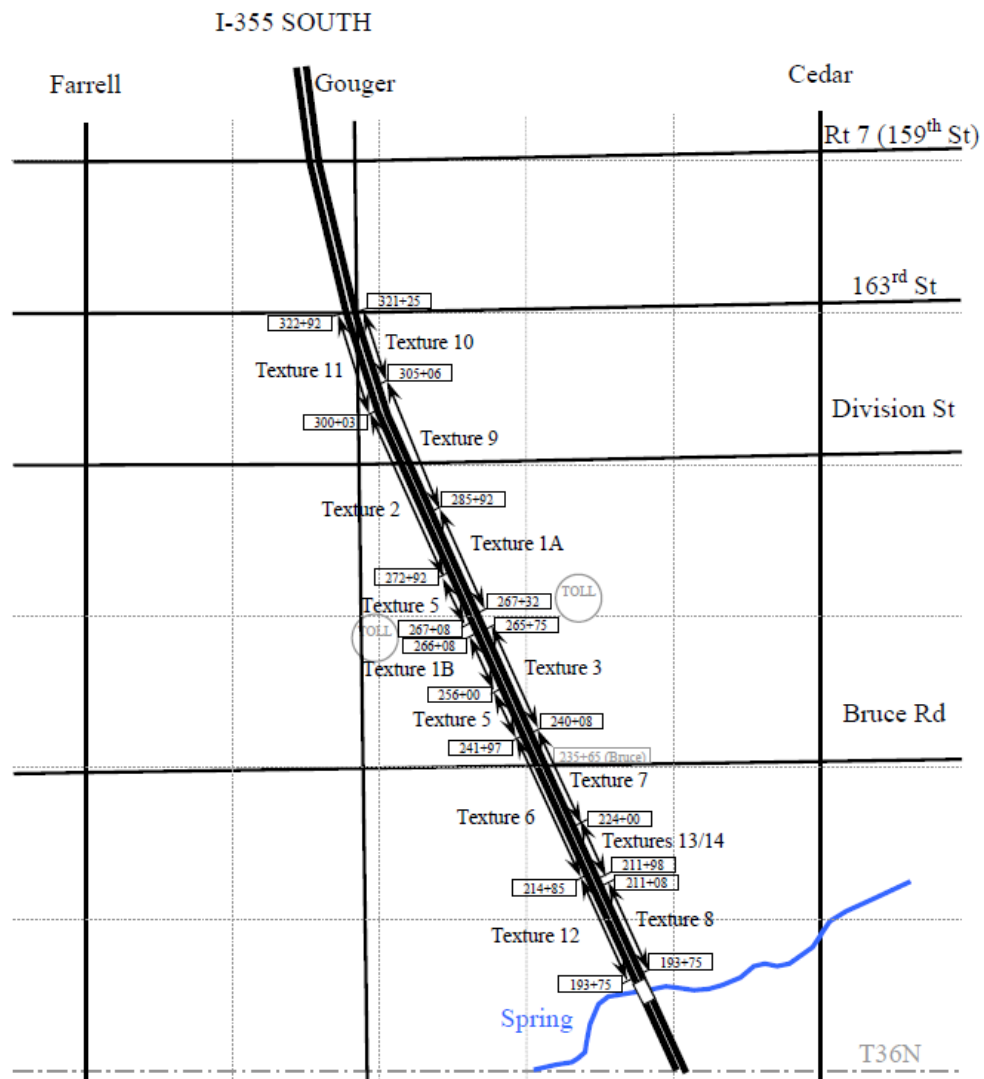


Figure 4.2: Texture types (labels) and segments on test site (Hall et al., 2009a).

Table 4.1: Texture types and numbering at test site (Hall et al., 2009a).

Texture No.	Texture description
1a	Longitudinal heavy turf drag (mean texture depth of 0.4 - 0.8 mm)
1b	Longitudinal heavy turf drag (mean texture depth of 0.6 – 1.1 mm)
2	Longitudinal tine (spacing $\times$ depth = 19×3.2 mm), no secondary texture
3	Longitudinal diamond grind (spacing $\times$ depth = 6×2.8 mm), no secondary texture
5a	Longitudinal tine (spacing $\times$ depth = 19×3.2 mm), turf drag
5b	Longitudinal tine (spacing $\times$ depth = 19×3.2 mm), heavy turf drag
6	Longitudinal shallow tine (spacing $\times$ depth = 19×2 mm), turf drag
7	Longitudinal groove (spacing $\times$ depth = 19×6.4 mm), burlap drag
8	Longitudinal groove (spacing $\times$ depth = 19×6.4 mm), turf drag
9	Transverse tine (spacing $\times$ depth = 12.5×3.2 mm), burlap drag
10	Transverse tine (spacing $\times$ depth = $10\text{-}21 \times 3.2$ mm), burlap drag
11	Transverse tine (spacing $\times$ depth = 25.4×3.2 mm), burlap drag
12	Transverse skewed random tine (spacing $\times$ depth = $17\text{-}54 \times 3.2$ mm), turf drag

Table 4.2: Field data at test site (Hall et al., 2009a).

Texture No.	MPD _{HSTP} ¹ (mm) from high-speed texture profiler	MPD _{CTM} ¹ (mm) from circular track meter	SI noise ² dB(A)	F(60) _{DFT} ³
1a	0.40	Not available	101.55	23.1
1b	0.32	0.28	101.79	19.9
2	0.71	0.60	103.23	23.9
3	0.35	0.65	100.48	22.8
5a	0.55	0.51	102.35	21.1
5b	1.22	1.02	105.31	30.8
6	0.54	0.49	102.20	21.2
7	1.04	1.02	101.69	30.5
8	0.98	1.22	102.47	34.6
9	0.48	0.48	102.63	23.6
10	0.62	0.62	102.85	23.4
11	0.50	0.44	104.07	20.9
12	0.64	0.58	102.69	23.5

¹ Mean values based on right wheel path and lane centre measurements.

² Sound intensity (SI) noise based on AASHTO TP076

³ Friction Number from Dynamic Friction Tester (DFT). Values substantially lower than expected.

4.3 3D Texture Parameters and Discussions

As defined in section 3.3 texture amplitude related 3D parameters were calculated for all the six spots of each texture type. The average value of the six spots of each texture was reported. The 3D texture parameters for all the 13 texture types are shown in Table 4.3. In general, $SMTD$ and S_q vary by texture type. As expected, the skewness for all the texture types except texture No. 3 is negative. The kurtosis in all cases is greater than three which indicates peaked distribution of texture. In summary, it is typical for pavements to have a peak and negatively skewed texture because of pavement construction with paver and roller, and surface treatment to enhance texture. Figure 4.3 shows the calculated SMTDs and their confidence intervals for various texture types.

As can be seen from Table 4.3 and Figure 4.3, a significant amount of variation of the calculated texture parameters was experienced for all the 13 types of textures. This observation is not surprising as it was also confirmed by other researchers (Hall et al., 2009a, Ahammed and Tighe, 2008a). This variation is due mainly to the construction variability of primary texture pattern, the random variations of secondary texture, and the white noise of texture measurement and recovering. Given that the 3D texture parameters were calculated based on an area of 100×100 mm for each texture type, multiple measurements (six replicate measurements in this research) are essential to have representative texture indices for each texture type.

4.3.1 Relating 3D to 2D Texture Parameters

The relationship between MPDs from CTM, high-speed texture profiler, and calculated 3D parameters from the recovered texture heights are analyzed. Figure 4.4 shows the relationship between mean profile depth from CTM (MPD_{CTM}) and simulated mean texture depth (SMTD) for the 12 available texture types. The only outlier is from texture No. 8

Table 4.3: 3D texture parameters for various texture types.

Texture No.	SMTD (mm)			S_q (mm)			S_{sk}			S_{ku}		
	μ (mm)	σ (mm)	c_v (%)	μ (mm)	σ (mm)	c_v (%)	μ (mm)	σ (mm)	c_v (%)	μ (mm)	σ (mm)	c_v (%)
1a	0.58	0.24	41	0.13	0.05	39	-0.08	0.30	330	3.36	0.52	16
1b	0.38	0.06	17	0.10	0.01	6	-0.13	0.32	246	3.43	0.36	11
2	0.91	0.15	17	0.43	0.13	30	-1.20	0.26	22	4.13	0.64	16
3	0.82	0.24	29	0.18	0.04	21	0.70	0.11	166	3.16	0.46	15
5a	0.91	0.23	25	0.40	0.13	32	-1.33	0.16	12	4.78	0.74	16
5b	1.40	0.18	13	0.50	0.11	22	-0.97	0.25	25	4.10	0.57	14
6	0.49	0.04	9	0.20	0.05	25	-1.17	0.36	31	4.54	0.48	11
7	1.32	0.38	29	0.79	0.07	9.5	-1.53	0.26	17	4.58	0.56	12
8	1.10	0.24	22	0.76	0.15	20	-1.68	0.07	4	4.92	0.32	7
9	0.63	0.11	18	0.21	0.06	26	-1.00	0.24	25	4.17	0.59	14
10	0.69	0.09	14	0.28	0.02	7.5	-1.04	0.11	11	4.13	0.42	10
11	0.58	0.14	25	0.21	0.04	20	-1.60	0.23	14	6.70	1.16	17
12	0.87	0.19	22	0.33	0.10	32	-1.62	0.19	12	7.64	1.74	23

Notes: μ = Mean value of the six replicate measurements

σ = Standard deviation

$c_v = \mu / \sigma$, coefficient of variation

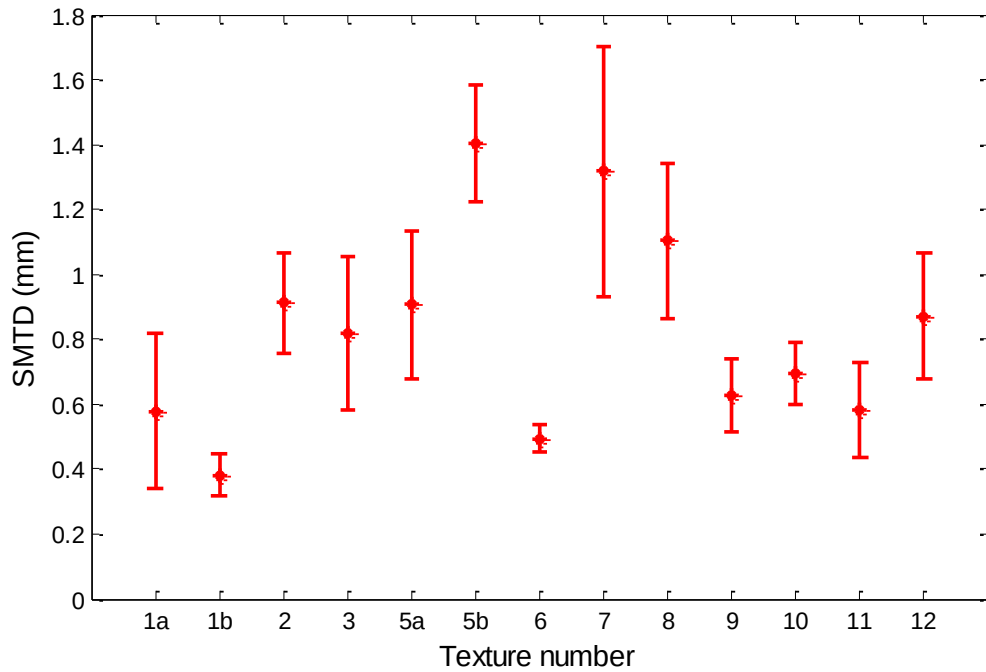


Figure 4.3: Calculated SMTDs and their confidence intervals.

(longitudinal groove with turf drag). Similar issues are found for texture No. 8 in Figure 4.8 which shows the relationship between SMTD and Friction Number $F(60)$ from DFT. These observations imply either the texture measurement using CTM or DFT test for texture No. 8 has unusual error.

Figure 4.5 shows the relationship between MPD from high-speed texture profiler (MPD_{HSTP}) and SMTD for all the 13 texture types.

As can be seen from Figure 4.4 and Figure 4.5, a significant relationship ($R^2 = 0.67$) is found between the SMTD and MPD from the CTM. A stronger relationship ($R^2 = 0.77$) is found between SMTD and MPD from high-speed texture profiler.

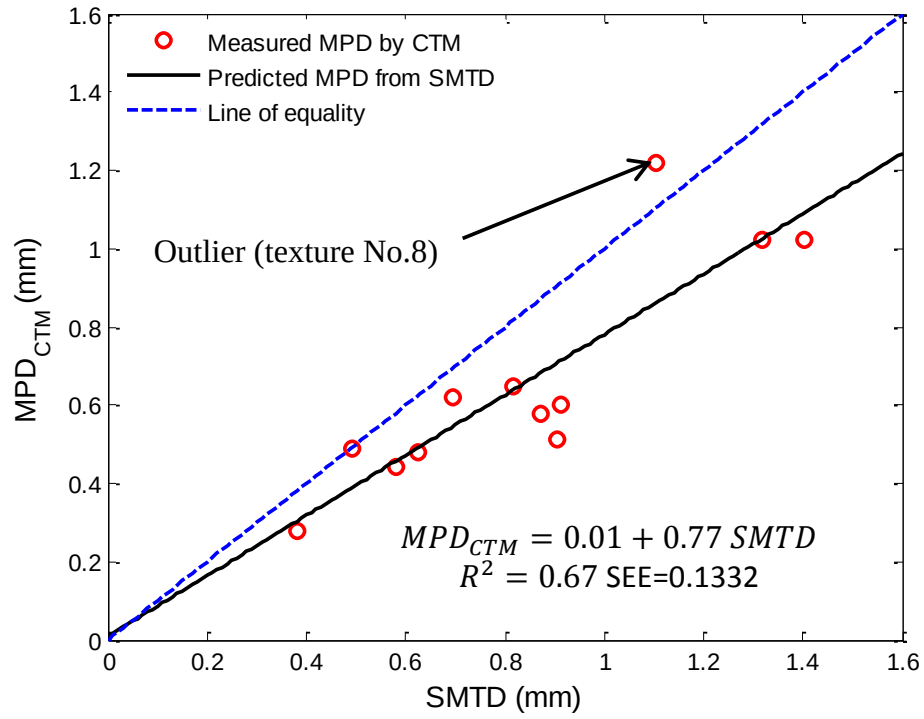
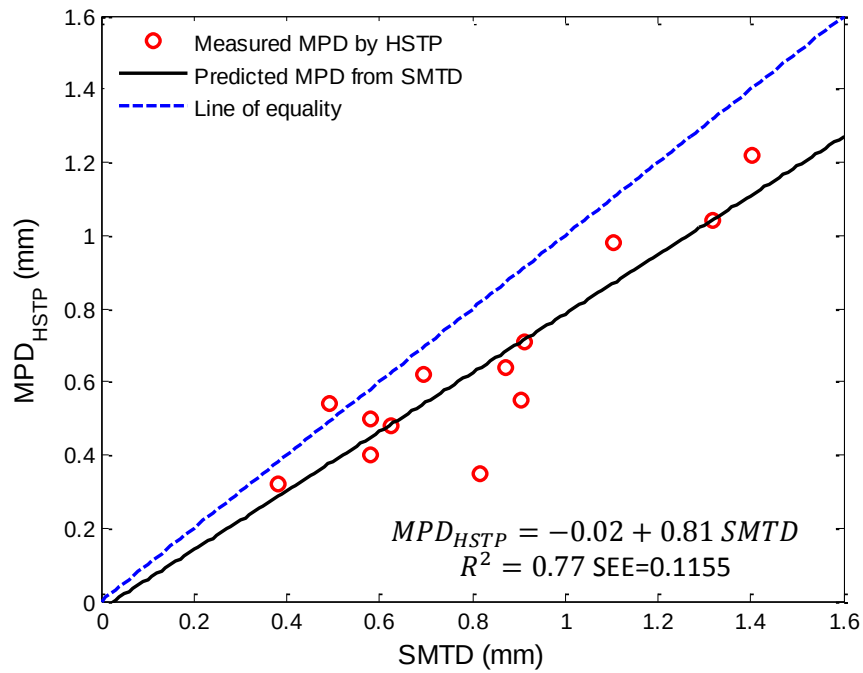
This observation implies that 2D based MPD is an estimate of 3D texture heights, that the photometric stereo method is valid to recover pavement texture in 3D manner, and that 2D and 3D macrotexture depths are convertible in terms of data comparison or quality assurance among agencies in case their equipment is of different dimensions.

4.3.2 Relationship between Skewness and Kurtosis

Figure 4.6 shows the relationship between skewness and kurtosis for longitudinal texture. A strong correlation with R^2 value of 0.90 is found between skewness and kurtosis. This is not surprising because skewness and kurtosis are based on the third and fourth moment of surface texture heights. This observation suggests that either of skewness or kurtosis is sufficient to describe the shape and distribution of the texture in this application.

4.3.3 Evaluating Noise Generated by Longitudinal Texture

Correlation analysis between texture indices and sound intensity (SI) noise was conducted for longitudinal texture only in this research due to the following reasons: 1. Noise characteristic for longitudinal and transverse texture is different (Burge et al., 2002, Donovan,

Figure 4.4: Relationship between MPD_{CTM} and SMTD.Figure 4.5: Relationship between MPD_{HSTP} and SMTD.

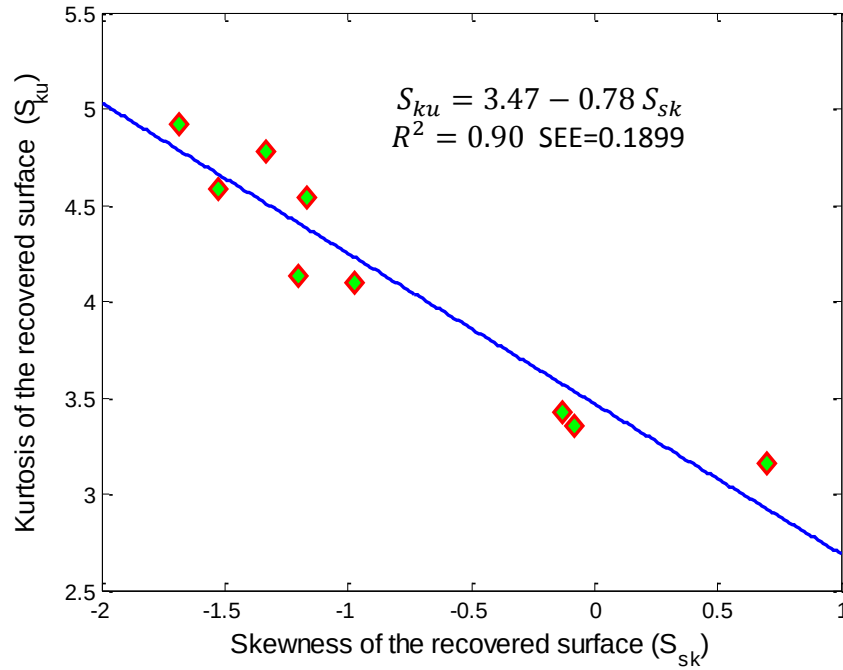


Figure 4.6: Relationship between skewness and kurtosis for longitudinal texture.

2006); 2. Noise data are available only for four types of transverse texture in this research, which limits meaningful regression analysis.

The SI noise and SMTD for the longitudinal textures is plotted as shown in Figure 4.7 (a). No significant relationship can be found between SI noise and SMTD although the larger SMTD generally related to higher SI noise as the trend line implies as can be seen from Figure 7(a). This is not surprising in lieu of the literature review (Hall et al., 2009a, Kuemmel et al., 2000).

The skewness of longitudinal texture can be divided into two groups as shown in Figure 4.7 (b). Group 1 includes textures where their skewness is positive or negative but close to zero, while group 2 includes textures where their skewness is negative and less than a threshold value, $S_{sk} \leq -0.5$, for instance.

A regression analysis for group 2 textures was conducted among SI noise, SMTD, and skewness as shown in Equation (4.1).

$$\begin{aligned} \text{Noise} &= 105.87 + 2.06\text{SMTD} + 3.88S_{sk} \\ R^2 &= 0.71 \quad SEE = 0.559 \end{aligned} \tag{4.1}$$

Where

Noise = predicted onboard sound intensity noise,

SMTD = simulated mean texture depth,

S_{sk} = skewness of the recovered texture height map,

R^2 = coefficient of determination,

SEE = standard error of the estimate.

As can be seen from Equation (4.1), the distribution and shape of the texture represented by skewness (S_{sk}) is one of the major contributors to the SI noise, as well as texture depth represented by SMTD in this research. The larger the mean texture depth, the noisier the pavement will be. The more negatively skewed texture will make the pavement quieter, which agrees with findings from another study (Rasmussen et al., 2007). The author was aware of the limitations of the data available in this research. More tests are required to confirm or reject this observation.

4.3.4 Evaluating Friction

Figure 4.8 shows the relationship between the computed SMTD and Friction Number F(60) from DFT tests. It suggests that F(60) can partially be predicted with an R^2 value of 0.52 by using SMTD for various texture types. This observation indicates that the mean macrotexture depth is one of the main contributors to pavement friction, which agrees with other studies (PIARC, 1995, Hall et al., 2009b). Again, the main outlier is from texture No. 8 similar to the issue presented in Figure 4.4. According to NCHRP Report 634, the original friction measurements of this texture had larger variations than that of other textures (Hall et al., 2009a).

The predicted friction number F(60) is shown in Equation (4.2) if both SMTD and

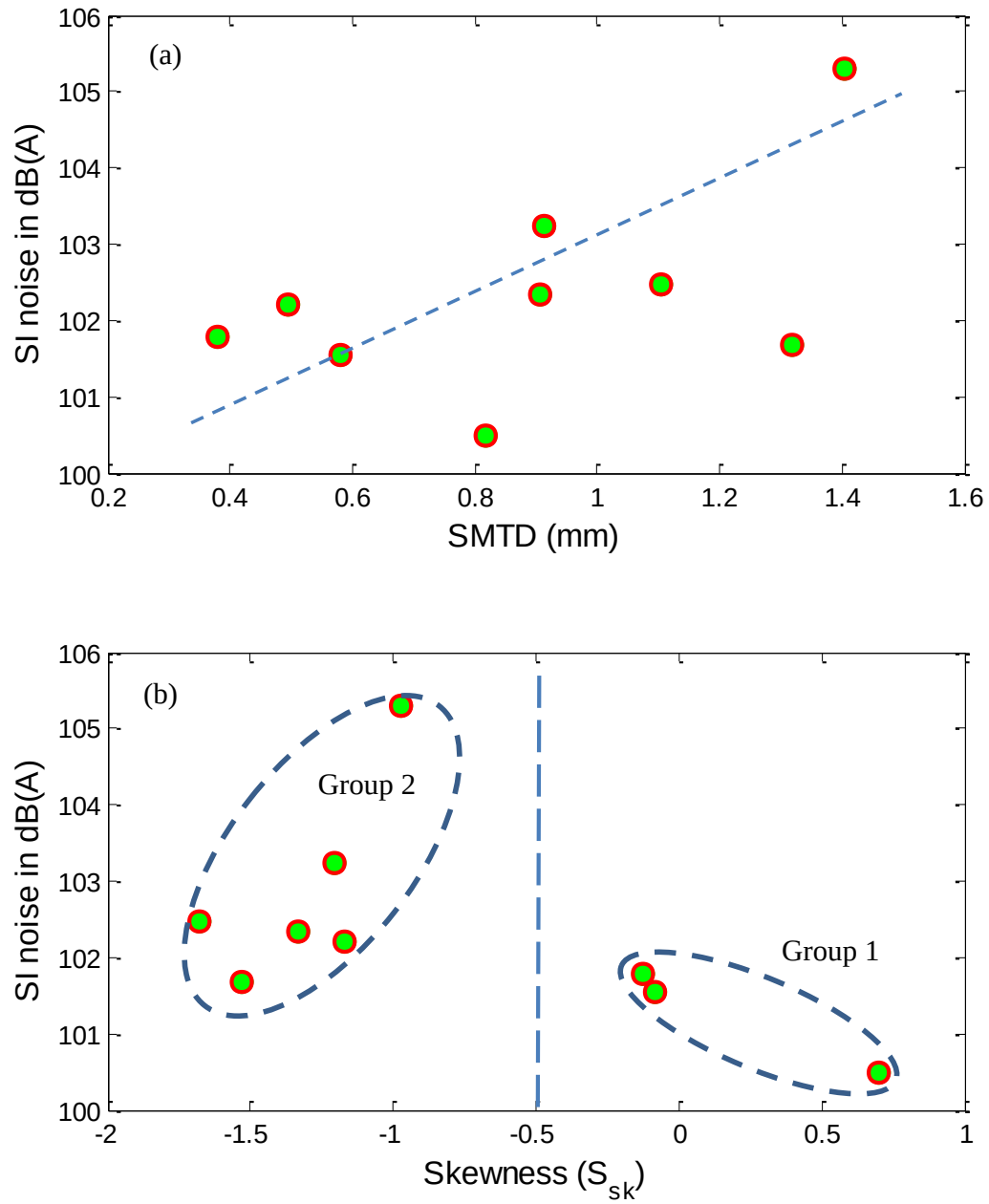


Figure 4.7: Sound intensity noise versus (a) SMTD (b) skewness: Group 1 ($S_{sk} > -0.5$), Group 2 ($S_{sk} \leq -0.5$).

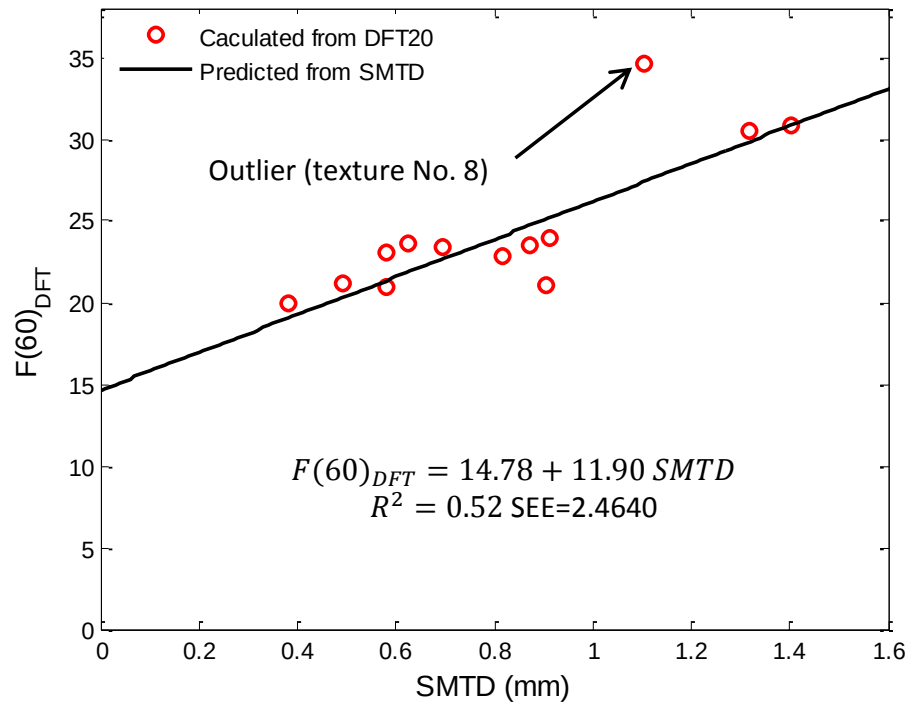


Figure 4.8: Relationship between F(60) from DFT and SMTD.

skewness are included.

$$F(60) = 14.64 + 11.54 SMTD - 0.45 S_{sk} \quad (4.2)$$

$$R^2 = 0.53 \quad SEE = 2.4472$$

Where

F(60) = Friction number,

Other variables are as defined previously.

As can be seen from Equation (4.2), the prediction of F(60) is slightly better than that shown in Figure 4.8. In addition to SMTD, the negative skewness of the texture is another contributor to the friction values. The negatively skewed texture is helpful to drain the applied water away during DFT testing and to have higher friction value of the tested pavement. However, it is not sufficient to predict pavement friction by using macrotexture indices only. This observation agrees with finding from other researchers (Do et al., 2000,

Flintsch et al., 2003b) that both microtexture and macrotexture measurements are needed for adequate frictional prediction.

4.3.5 Influence of Texture on Noise and Friction

By comparing Equation (4.1) and Equation (4.2), it was found that pavement noise and friction could be partially predicted by using 3D macrotexture indices, and that the prediction of SI noise was better than that of friction by using SMTD and skewness. This observation indicated that macrotexture is a more dominant factor of pavement exterior (sound intensity) noise comparing to pavement friction. These observations agree with findings from other studies (Henry, 2000, Sandburg and Ejsmont, 2002a).

By using the proposed noise and friction models represented by Equation (4.1) and Equation (4.2), the predicted pavement noise, friction, and texture ranking for pavement with longitudinal texture and S_{sk} less than -0.5 were shown in Table 4.4.

Table 4.4: Predicted noise and friction for longitudinal texture with $S_{sk} \leq -0.5$.

Texture No.	Brief texture description ¹	SMTD (mm)	S_{sk}	Predicted value ²		Criterion (noise/friction)	Ranking
				noise dB(A)	friction		
7	groove + burlap	1.32	-1.53	102.65	30.56	3.359	1
5b	tine + heavy turf	1.40	-0.97	104.99	31.23	3.362	2
8	groove + turf	1.10	-1.68	101.62	28.09	3.618	3
5a	tine + turf	0.91	-1.33	102.58	25.74	3.985	4
2	tine	0.91	-1.20	103.09	25.68	4.014	5
6	shallow tine + turf	0.49	-1.17	102.34	20.82	4.915	6

¹-- Refer to Table 1 for detailed texture description

²—Predicted from Equations (4.1) and (4.2)

Based on the evaluation criterion of the noise/friction ratio as shown in Table 4.4, the top three textures are texture No. 7, No. 5b, and No. 8. In general, texture with larger SMTD related to higher friction and higher noise. The negatively skewed texture is appropriate to pavement surface. The more negatively skewed texture will provide higher

friction and lower noise to the pavement. Both primary and secondary textures have significant impacts on pavement noise/friction.

The proposed 3D texture parameters and regression models in this study provide texture descriptors and low cost tools to evaluate pavement noise and friction. These findings are useful to design and build quiet and safe PCC pavements.

4.4 Summary of Findings

Three-dimensional macrotexture indices were proposed and calculated from the recovered pavement surface texture height map by using photometric stereo method. A relationship with an R^2 value of 0.67 and 0.77 was developed between SMTD from the photometric stereo method and MPD from the CTM and the high-speed texture profiler, respectively. The SMTD from photometric stereo method is compatible with MPD from 2D texture measurements. SMTD from the recovered 3D texture heights is a good indicator of the amplitude of pavement macrotexture. The skewness and kurtosis represent the pavement texture direction and shape of the texture distribution.

Regression analysis between pavement noise/friction and 3D texture indices was conducted. A relationship with an R^2 value of 0.71 was developed between pavement sound intensity noise and 3D texture indices (SMTD and Skewness). The R^2 value was 0.53 between pavement friction [F(60)] and 3D texture indices (SMTD and Skewness). The pavement noise and friction can partially be explained by using the proposed 3D macrotexture parameters although macrotexture itself is not a sufficient descriptor for adequate prediction of pavement friction or noise.

Both texture heights (SMTD) and texture distribution (skewness and kurtosis) are important factors in pavement noise/friction. In addition to texture amplitude represented by SMTD, the pavement texture direction and shape of the texture distribution, represented

by skewness and kurtosis, have strong impacts on pavement noise and friction. Negatively skewed surface texture is appropriate to pavement with higher friction and lower noise. The proposed 3D texture parameters and regression analysis in this study provide texture indices and low cost tools to evaluate pavement noise and friction. These findings are useful to design and build quiet and safe PCC pavements. It is possible to have a better understanding of texture characteristics and pavement noise/friction by using the combination of 3D parameters, SMTD, skewness, or kurtosis of the pavement surface.

Chapter 5

3D AND CIRCULAR TRACK METER TEXTURE MEASUREMENTS AT MnROAD TEST FACILITIES

5.1 Introduction

As discussed in section 2.1.2, various types of equipment have been employed to evaluate pavement texture, and their differences of reported texture parameters can be significant (Hall et al., 2009a), thereby making it difficult to conduct effective pavement texture assessment. Researchers (El Gendy and Shalaby, 2007, El Gendy et al., 2011, Bitelli et al., 2012) found that 2D texture measurement and texture indicators are insufficient to represent texture especially when friction or noise is studied. While the 2D attribute can be correlated to friction and noise, it is not the only contributing factor. Texture height, spacing, and distribution should also be considered.

Therefore advanced tools that characterize pavement texture using 3D texture measurement should be evaluated to provide more realistic and comprehensive assessment of pavement texture (TRB-AFD90, 2013, 2010). Numerous studies (Vilaça et al., 2010, Huang et al., 2010, Abbas et al., 2007, Kim et al., 2013) have been conducted on 3D pavement surface texture measurement. These studies were also compared their MPDs with MTDs from the traditional sand patch method (which is sensitive to operator's variability). To the author's knowledge, however, no document is available that conducted correlation analysis between 3D and 2D texture parameters from laser based measurement devices.

The objectives of this chapter are to compare pavement texture measurements collected simultaneously from two devices, a 3D line-laser areal surface scanner and 2D circular track meter (CTM), and to assess whether correlations exist between their texture

parameters. Simultaneous line-laser scanner and CTM testing were conducted on six pavement cells at the Minnesota Department of Transportation MnROAD test facility to compare the 3D and 2D texture measurements. This chapter presents the results of the analysis and the relationship between the parameters from the two devices. The findings in this research can be used to convert texture indices between 2D and 3D measurements for the purposes of data comparison or quality assurance among agencies in case their equipment is of different dimensions.

5.2 Line-Laser Scanner and Circular Track Meter (CTM)

As introduced in section 2.2.2, the line-laser scanner produces 3D surface texture measurements with a horizontal resolution finer than 0.05 mm, and covering both surface micro- and macrotexture ranges.

The advantages of the line-laser scanner are that pavement surface texture is recovered into 3D surface texture height maps, instead of a single 2D profile from devices such as the CTM, and providing more realistic assessment of surface texture. The CTM is a non-contact spot-laser device that measures 2D surface texture profile (ASTM E2157, 2009), and reduces the 2D texture data to a single attribute such as mean profile depth (MPD).

The line-laser scanner and the CTM used in this research are shown in Figure 5.1. A comparison of the features of the two devices is summarized in Table 5.1. The resolution of the line-laser scanner is approximately 17 times finer than that of the CTM. The line-laser scanner can produce indices from 3D texture heights for both micro and macro pavement texture, while the CTM measures macrotexture only.

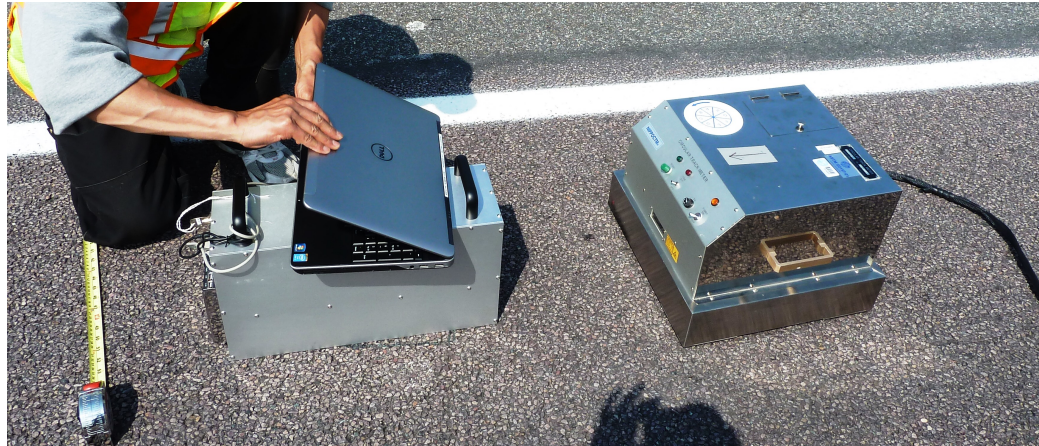


Figure 5.1: Texture devices: a line-laser scanner (a) and a circular track meter (b).

Table 5.1: Features of line-laser scanner and circular track meter (CTM).

Device	Line-laser scanner	Circular Track Meter
Laser	Line laser	Spot laser
Sample interval (mm)	<0.05	0.87
Vertical accuracy (mm)	<0.05 (Lab calibration)	0.03 (Std. of 8 measurements)
Wavelength bands	Microtexture, Macrotexture	Macrotexture
Texture map dimensions	3D	2D
Macrotexture indices	SMTD , Skewness, Kurtosis, S_q	MPD, RMSR
Method of measurement	Stationary	Stationary
Standard/specification	No standard	ASTM E 2157
Attributes	Indices from 3D texture heights	Indices from 2D texture profile

Note: SMTD=Simulated mean texture depth
 RMSR=Root mean square roughness
 MPD=Mean profile depth
 S_q =Root mean square deviation of the surface

5.3 Pavement Texture Measurement at MnROAD Test Facilities

MnROAD, located near Albertville, Minnesota (40 miles northwest of Minneapolis-St. Paul) is one of the most sophisticated, independently operated pavement test facilities of its type in the world. The two major components are: MnROAD mainline test section and Low Volume Road (LVR) (MnROAD, 2012) as can be seen in Figure 5.2. As of October, 2013, there are 36 test cells on LVR section and 40 test cells on Mainline section. MnROAD field performance data includes the results from the following tests: sand patch, circular track meter (CTM), friction test, and onboard sound intensity (OBSI). Those data are useful to validate the results from this research and for further analysis.



Figure 5.2: MnROAD test facilities (Izevbekhai, 2012).

In June 2014, simultaneous line-laser scanner and CTM testing were conducted on six pavement cells at the MnROAD test facility to compare 3D and 2D texture measurements. Surface textures were measured on six pavement cells from the MnROAD Mainline and Low Volume Road segments. The tested surfaces include rigid, flexible, and composite

pavements. Six replicate texture measurements were conducted for each tested cell simultaneously using both line-laser scanner and CTM, for a total of 36 measurements per device. The pavements included Portland cement concrete (PCC) and asphalt concrete (AC) surfaces with various textures. The surface texture descriptions of the MnROAD cells measured are shown in Table 5.2. To facilitate the visualization of the tested pavement texture, Figure 5.3 shows the pavement texture of the 6 AC and PCC surfaces.

For each test cell of the Mainline segment, measurements were taken at three stations in both the driving and passing lanes. For the test cell at the LVR segment, measurements were taken at three stations in the inside and outside lanes. As an example, the three pavement texture measurement stations for cell 2 are shown in Figure 5.4. Figure 5.5 shows AC surface of Cell 22, its recovered 3D texture height map plotted from the line-laser scanner, and recovered 2D texture profile plotted from the CTM.

Table 5.2: Tested cells and surface texture description at MnROAD .

Segment	Cell number	Surface type	Surface age (year)	Description of surface texture
Mainline I-94	2	AC	6	Ultra-thin bonded wearing course
	22	AC	6	12.5 mm dense graded Superpave
	13	PCC	5	Longitudinal turf drag
	71	PCC	4	Ultimate longitudinal diamond grind for driving lane, conventional longitudinal diamond grind for passing lane
	505/605	PCC	3	Unbonded PCC overlay with transverse broom
Low Volume Road	140/240	PCC	1	Unbonded PCC overlay with thin/standard fabric, transverse tine (The inside lane is trafficked with a 5-axle semi and the outside lane is left for environmental loading with no truck traffic)

Note: AC=asphalt concrete, PCC=Portland cement concrete

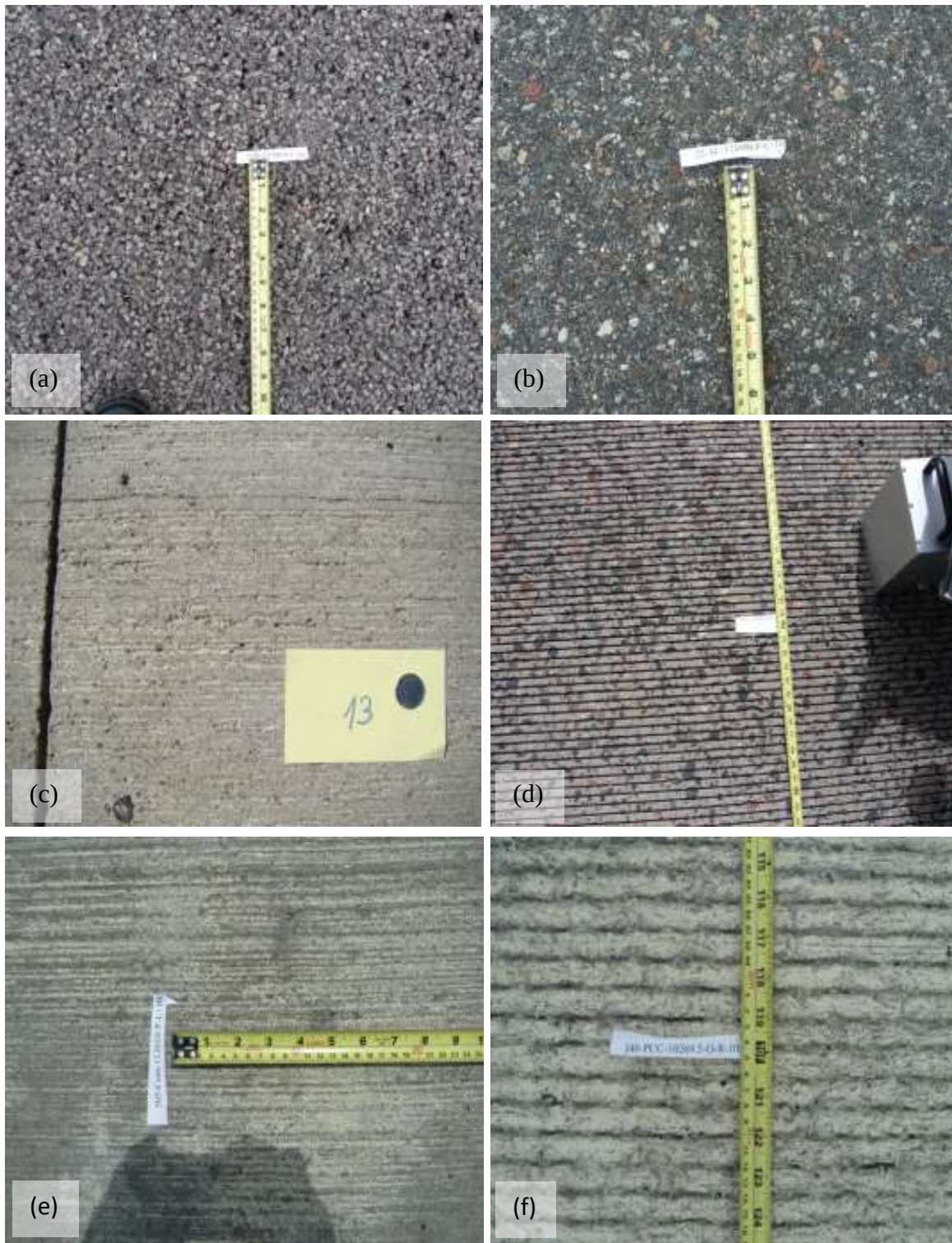


Figure 5.3: Pavement texture of (a) AC surface of Cell 2, (b) AC surface of Cell 22, (c) PCC surface of Cell 13, (d) PCC surface of Cell 71, (e) PCC surface of Cell 505/605, and (f) PCC surface of Cell 140/240.

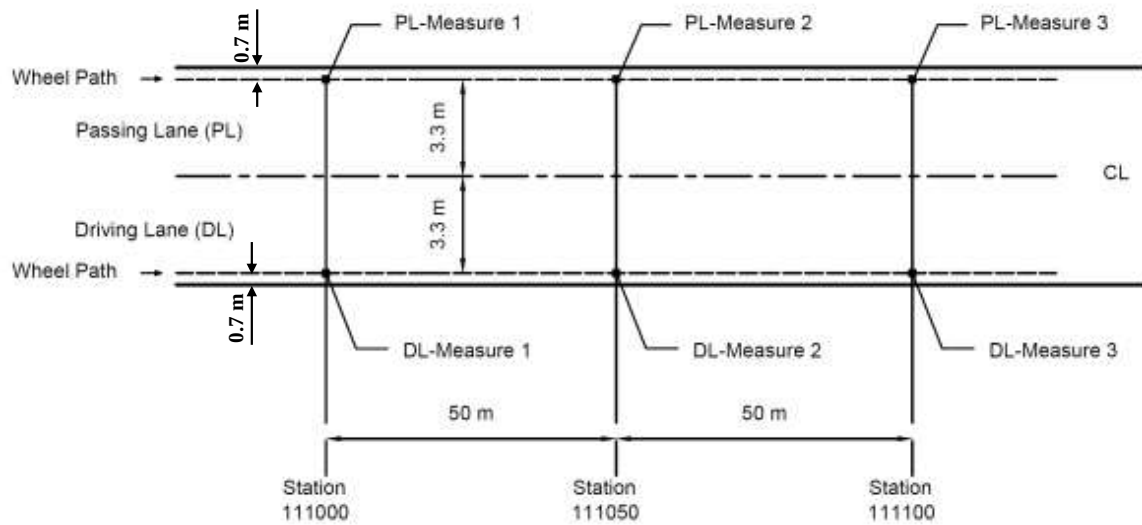


Figure 5.4: Pavement texture measurement stations for test cell 2.

5.4 Comparing 3D and 2D Macrotexture Parameters

Four macrotexture parameters from the 3D line-laser scanner, simulated mean texture depth (SMTD), root mean square deviation (S_q), Skewness (S_{sk}), and Kurtosis (S_{ku}) were calculated from texture heights after the discrete wavelet transform (DWT) as discussed in section 3.2. The macrotexture parameters are based on the first, second, third, and fourth moment (power) of the macrotexture heights after DWT analysis from the line-laser scanner. The 3D texture parameters and their calculation formulas were discussed in section 3.3.

Two macrotexture parameters from the 2D CTM, mean profile depth (MPD) and root mean square roughness (RMSR), were calculated from the measured texture profiles following Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter (ASTM E2157, 2009).

Table 5.3 presents the calculated macrotexture parameters from the line-laser scanner and CTM measurements from the MnROAD pavement cells. In general, the line-laser scanner mean texture depth (SMTD) and root mean square deviation (S_q) varied by pave-

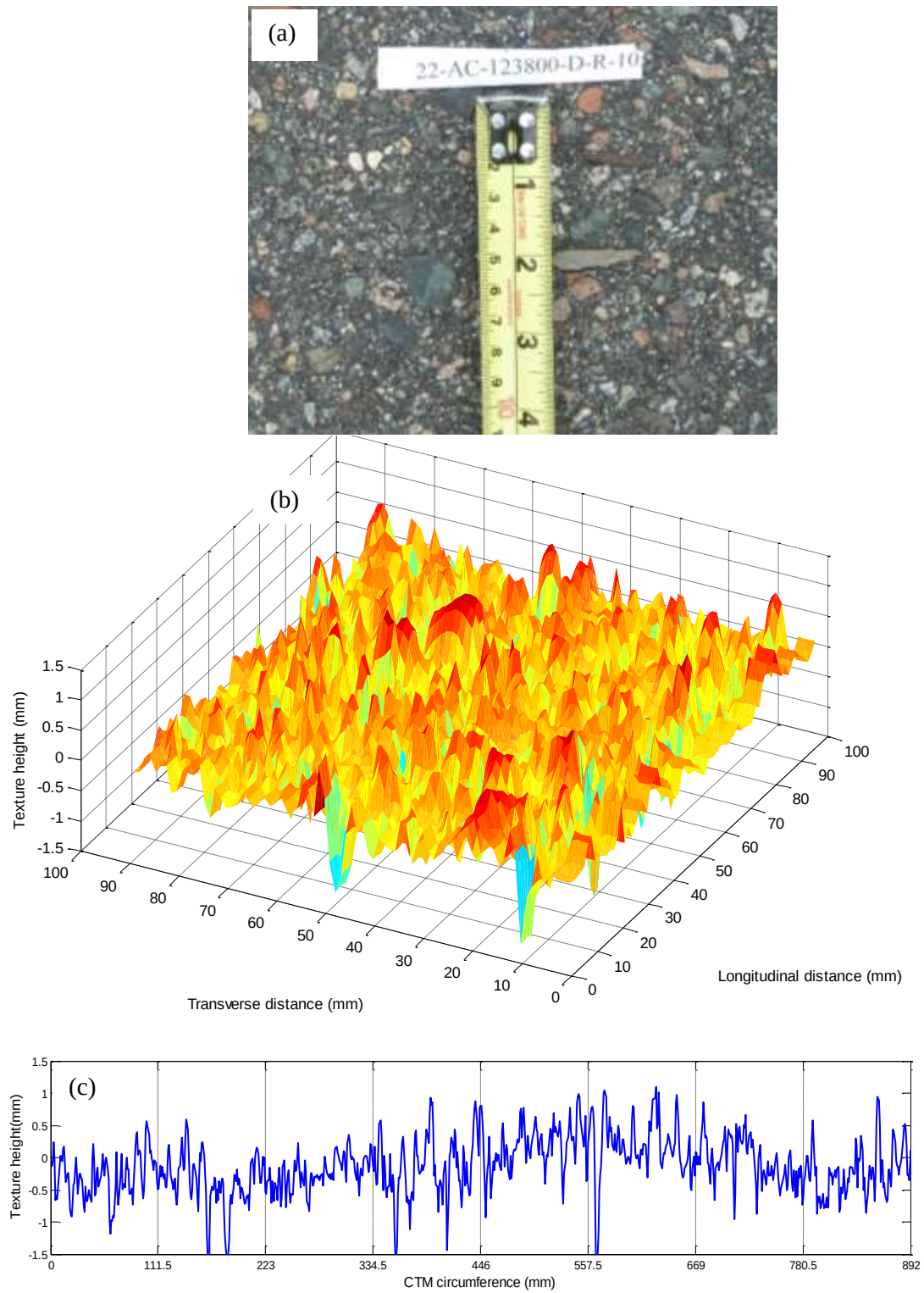


Figure 5.5: Pavement surface (a) pavement surface of Cell 22 (b) recovered 3D texture heights from line-laser scanner of Cell 22, and (c) recovered 2D texture profile from CTM of Cell 22.

ment surface type. The CTM mean profile depth (MPD) and root mean square roughness (RMSR) also varied by pavement surface type. The line-laser scanner macrotexture parameters show the skewness (S_{sk}) is negative for all pavement cells, which implies that the tested textures are negatively skewed, with PCC pavements having larger negative skewness than AC pavements. Possible reasons for the negatively skewed distributions include the method of construction (paving and compaction, tining), traffic polishing effect on texture, or voids created by ravelling. The kurtosis is greater than 3 for all pavement cells except for 2 measurements on the passing lane of cell 71 which is less than 3. This kurtosis observation indicates that the pavement textures are peaked distribution. A kurtosis >3 indicates the surface is dominated by sharp peaks (spikes), while a kurtosis <3 indicates flatter peaks.

A linear regression model was developed between the MPD from the CTM and the SMTD from the line-laser scanner. Equation (5.1) shows the relationship between the SMTD and MPD.

$$MPD = \alpha_1 + \beta_1 \times SMTD \quad (5.1)$$

Where

MPD = mean profile depth from circular track meter,

$SMTD$ = simulated mean texture depth from line-laser scanner,

α_1, β_1 = regression parameters.

Table 5.4 presents the coefficients and statistical parameters of the regression model. A significant relationship ($R^2 = 0.83$) is found between the MPD from the CTM and the SMTD from the line-laser scanner. A t-test was carried out to test the null hypothesis that the coefficients are not statistically different from zero at 95% confidence level. As can be seen from Table 5.4, since t-critical is less than the t-statistic, the model coefficients are significant. Additionally, since the p-value, which is the probability that the null hypothesis

Table 5.3: Texture parameters from line-laser scanner and CTM for tested cells.

Segment	Cell no.	Lane	Test station	Line-laser Scanner		Circular Track Meter	
				SMTD (mm)	S _q (mm)	MPD (mm)	RMSR (mm)
Mainline I-94	2	Driving	111000	2.31	0.88	1.27	0.93
			111050	2.82	0.87	1.15	0.85
			111100	2.70	0.90	1.21	0.98
		Passing	111000	2.49	1.06	1.52	1.13
			111050	2.43	1.10	1.42	1.18
			111100	2.58	1.03	1.33	0.99
	22	Driving	123700	0.75	0.24	0.52	0.24
			123750	0.80	0.27	0.59	0.29
			123800	0.74	0.22	0.49	0.27
		Passing	123700	1.42	0.37	0.71	0.37
			123750	1.18	0.26	0.61	0.27
			123800	1.08	0.31	0.58	0.32
	13	Driving	118660	1.11	0.61	0.59	0.53
			118710	1.11	0.66	0.66	0.62
			118800	1.50	0.96	0.85	0.88
		Passing	118660	1.46	0.77	0.99	0.79
			118710	1.37	0.98	0.94	0.81
			118800	1.68	1.09	1.07	0.89
	71	Driving	117030	1.54	1.75	1.07	1.62
			117080	1.72	1.84	1.18	1.64
			117130	1.79	1.82	1.05	1.70
		Passing	117030	0.72	0.26	0.47	0.24
			117080	0.67	0.28	0.56	0.27
			117130	0.63	0.27	0.52	0.28
Low volume road	505/605	Driving	112700	0.69	0.23	0.45	0.33
			112750	0.68	0.19	0.38	0.30
			112800	0.55	0.25	0.35	0.21
		Passing	112700	1.12	0.40	0.53	0.34
			112750	0.72	0.23	0.40	0.28
			112800	0.86	0.25	0.50	0.31
	140/240	Outside	10280	2.28	0.61	0.92	0.53
			10330	N/A	N/A	1.25	0.74
			10380	1.08	0.20	0.36	0.21
		Inside	10280	2.66	1.07	1.18	0.90
			10330	2.17	1.03	1.18	0.91
			10380	1.38	0.36	0.59	0.33

Note: SMTD=Simulated mean texture depth
 RMSR=Root mean square roughness
 MPD=Mean profile depth
 S_q=Root mean square deviation of the surface
 N/A=Not available. The original data file was corrupted.

is rejected, is less than the confidence limit of 0.05, therefore the model coefficients are significant. An F-test was conducted at the 95% confidence level to determine the significance of the linear regression model. As can be seen from Table 5.4, since F-critical is less than F-statistic, and the p-value is less than the confidence limit of 0.05, the model is significant.

The statistical analysis indicates that the linear regression model is significant and can be used to convert SMTD to MPD, and that the DWT methodology in this research is valid. Other studies (Liu and Shalaby, 2014, Ejsmont et al., 2012) found that the correlation between MPD measured by the CTM and equivalent texture measurements by other devices had R^2 of 0.67 and 0.69, which are not as significant as this study.

Table 5.4: MPD and SMTD regression model and hypothesis test at 95% confidence.

Regression model		$MPD = \alpha_1 + \beta_1 \times SMTD$			
Coefficient	Estimate	Standard error	t-Statistic	t-Critical	p-Value (<0.05)
α_1	0.16177	0.05635	2.8708	2.0345	7.0971×10^{-3}
β_1	0.44374	0.03497	12.689	2.0345	3.0461×10^{-14}
Regression model		$MPD = 0.16 + 0.44 \times SMTD$			
Number of observations		35			
Root mean squared error		0.145			
R^2		0.83			
F-Statistic		161			
F-Critical		4.1393			
p-Value (<0.05)		3.05×10^{-14}			

A subsequent linear regression model was developed between the RMSR from the CTM and S_q from the line-laser scanner. Equation (5.2) shows the relationship between the RMSR and S_q .

$$RMSR = \alpha_2 + \beta_2 \times S_q \quad (5.2)$$

Where

$RMSR$ = root mean square roughness from circular track meter,

S_q = root mean square deviation from line-laser scanner,

α_2, β_2 = regression parameters.

Table 5.5 presents the coefficients and statistical parameters of the regression model. A significant relationship ($R^2 = 0.98$) was found between the $RMSR$ from CTM and the S_q from line-laser scanner. As can be seen from Table 5.5, the t-test, F-test, and p-values show the coefficients and regression model are significant. The statistical analysis indicates that the linear regression model is significant and can be used to convert $RMSR$ to S_q , and that the DWT methodology in this research is valid.

Table 5.5: $RMSR$ and S_q regression model and hypothesis test at 95% confidence level.

Regression model		$RMSR = \alpha_2 + \beta_2 \times S_q$			
Coefficient	Estimate	Standard error	t-Statistic	t-Critical	p-Value (<0.05)
α_2	0.04531	0.020484	2.2118	2.0345	0.03401
β_2	0.89531	0.024823	36.068	2.0345	4.32×10^{-28}
Regression model		$RMSR = 0.045 + 0.895 \times S_q$			
Number of observations		35			
Root mean squared error		0.07			
R^2		0.98			
F-Statistic		1300			
F-Critical		4.1393			
p-Value (<0.05)		4.32×10^{-28}			

The relationship between MPD from the CTM and SMTD from the line-laser scanner were plotted as shown in Figure 5.6. While the relationship is significant, the predicted MPD from the CTM is approximately 40% lower than the MTD3 from the line laser scanner, when compared to the line of equality. This has resulted since the MPD parameter from the 2D CTM measurements uses only the average of two peaks of the first and second halves over a 100 mm baseline (ASTM E1845, 2009), while the SMTD parameter from the 3D line-laser scanner measurements uses all of the data points over entire scanned area.

Figure 5.7 shows the plot of the relationship between RMSR from the CTM and S_q from line-laser scanner. The results show an improved relationship, compared to Figure 5.6, between the RMSR from the CTM and S_q from the line-laser scanner. This is because the RMSR parameters from the 2D CTM measurement use all the data points of the profiles, and the S_q parameter from the 3D line-laser scanner measurement again uses all of the data points over the scanned area.

Based on the analysis and correlations between the 2D and 3D measurements, the relationship between the root mean square roughness (RMSR) from the CTM, and S_q from the line-laser scanner (in Figure 5.7) is recommended for predicting the texture indices in case equipment is of different dimensions.

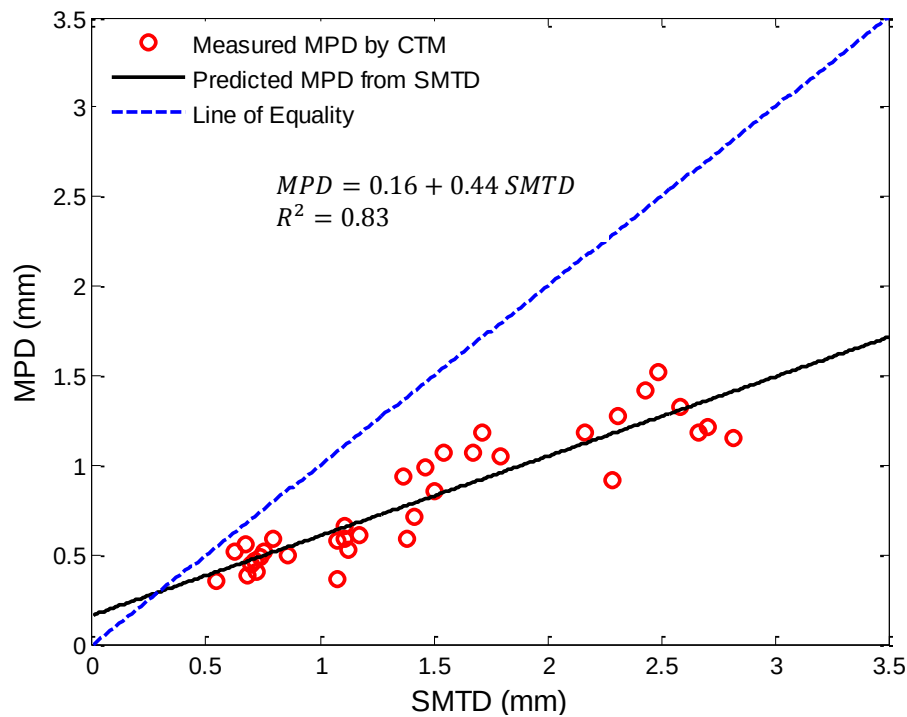


Figure 5.6: Relationship between MPD from CTM and simulated mean texture depth (SMTD) from line-laser scanner.

The results also show the MPD and SMTD of the driving lane are smaller than the corresponding values of the passing lane. Assuming the same initial as-built textures on

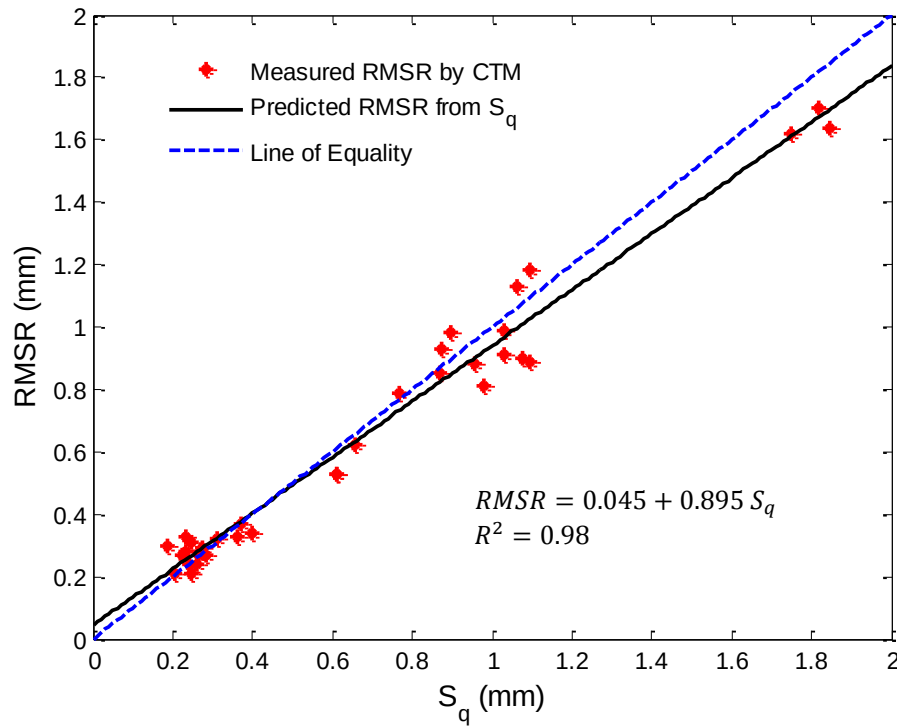


Figure 5.7: Relationship between RMSR from CTM and S_q from line-laser scanner.

both lanes, this observation indicates that the heavier traffic on the driving lane (which is approximately 2.5 times greater than the passing lane. Annual equivalent single axle load are reported as 678268 and 258228 for driving and passing lane, respectively) polishes the surface and breaks the texture at a higher rate than in the passing lane.

5.5 3D and 2D Macrotexture Parameters

A 3D line-laser scanner and a CTM were used to measure and compare the pavement texture parameters of six test cells at the MnROAD test facility. The recovered 3D texture heights from the line-laser scanner were transformed and decomposed to levels of micro-textures and macrotexture. Four macrotexture parameters were calculated after the transformation and decomposition of the recovered texture heights from the line-laser scanner. Two macrotexture parameters were calculated directly from the measured texture profiles

from the CTM.

The research showed that the typical pavement textures tested were negatively skewed, peaked distribution due to construction, traffic polishing, and environmental factors.

The research also showed that the calculated 3D texture parameters were highly correlated to the 2D texture parameters at the macrotexture level for the two devices. A relationship with an R^2 value of 0.83 was developed between the MPD from the CTM and the SMTD from the line-laser scanner. The root mean square roughness (RMSR) from the CTM is more strongly correlated ($R^2 = 0.98$) with the root mean square deviation (S_q) from the line-laser scanner. Mean profile depth (MPD), simulated mean texture depth (SMTD), root mean square roughness (RMSR), and S_q from the macrotexture are good indicators of pavement texture amplitude and variations. The relationship between the root mean square roughness (RMSR) from the CTM, and S_q from the line-laser scanner is recommended for the purposes of data comparison or quality assurance among agencies in case their equipment is of different dimensions.

The two laser devices, the 3D line-laser scanner and 2D CTM, produced similar macrotexture height parameters. This study validated the field performance of the 3D line-laser scanner and its macrotexture height parameters, SMTD and S_q . However, The 3D line-laser scanner can capture addition data for microtexture and additional indices for macrotexture, which makes the 3D line-laser scanner superior to the commercially available CTM.

Chapter 6

3D TEXTURE AND FRICTION ANALYSIS AT JAMES ARMSTRONG RICHARDSON INTERNATIONAL AIRPORT (WINNIPEG)

6.1 Introduction

Both the micro- and macrotexture characteristics of a runway surface can significantly affect measured friction values although measurements of pavement surface texture are not normally required by Civil Aviation Transport Canada (AC 302-017, 2014) . According to AC 302-017 and Aerodrome Standards and Recommended Practices (TP 312E, 2005), routine friction monitoring surveys need to be established by the airport operator so as to ensure the reliable identification of the need to take corrective action respecting the maintenance of coefficient of friction levels for all active runways. Transport Canada guidelines indicate that remedial action should be programmed for a facility when the overall runway average friction index falls below 60 or any 100 m section falls below 40 with a smooth tire friction measurement.

The objectives of this chapter are to classify and characterize runway surface texture by using a set of 3D texture indicators, and to explore the relationship between 3D runway pavement texture parameters and runway pavement friction. It is recommended that James Armstrong Richardson International Airport (Winnipeg) Authority considers using texture measurements as backup for friction data, and to investigate localized polished areas for which a friction testing has not been arranged.

6.2 Runway Pavement Surface Texture Measurement

The 3D surface texture heights of runway pavement were recovered using a line-laser scanner in cooperation with James Armstrong Richardson International Airport (Winnipeg) in October 2013. The test site was runway 13-31 of the James Armstrong Richardson International Airport. Based on the configuration of landing gears of various aircrafts, the texture and friction tests were conducted at 3 m, 6 m, and 15 m offsets of both left and right of the centreline of the runway. The surface pavement types of the test sites ranged from 10 years old asphalt concrete (AC) pavement, two year old AC pavement to two years old Portland cement concrete (PCC) pavement with longitudinal diamond grind, and two years old PCC pavement with transverse diamond groove.

As an example, Figure 6.1 shows the runway surface and texture measurement by using a line-laser scanner. Figure 6.2 shows one of the 2448 longitudinal profiles showing transverse diamond groove, while Figure 6.3 shows one of the 2048 transverse profiles showing longitudinal diamond grind. As shown in Figure 6.4, the runway pavement surface was recovered into a 3D texture height map.

Continuous friction tests of runways were conducted by others at the end of September 2013 using a trailer-mounted version of the International Civil Aviation Organization listed and Federal Aviation Administration /Transport Canada approved SARSYS Surface Friction Tester (SFT) (Taylor, 2013). SFT has been used to conduct the Transport Canada national test programs for more than 30 years. According to current standard Transport Canada test condition specifications, the friction tests with SFT were conducted at 65 km/h using a smooth-tread ASTM test tire at 200 kPa inflation pressure under self-watering conditions at 0.5mm water depth.

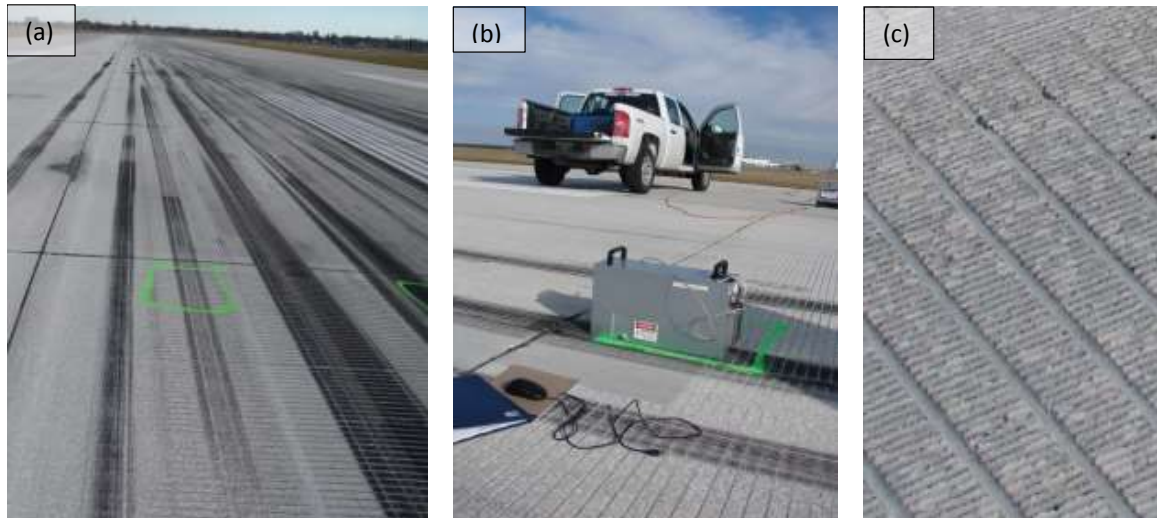


Figure 6.1: Runway texture measurement (a) general look of the pavement with transverse diamond groove and longitudinal diamond grind (b) measuring texture using a line-laser scanner (c) a close-up of the surface texture.

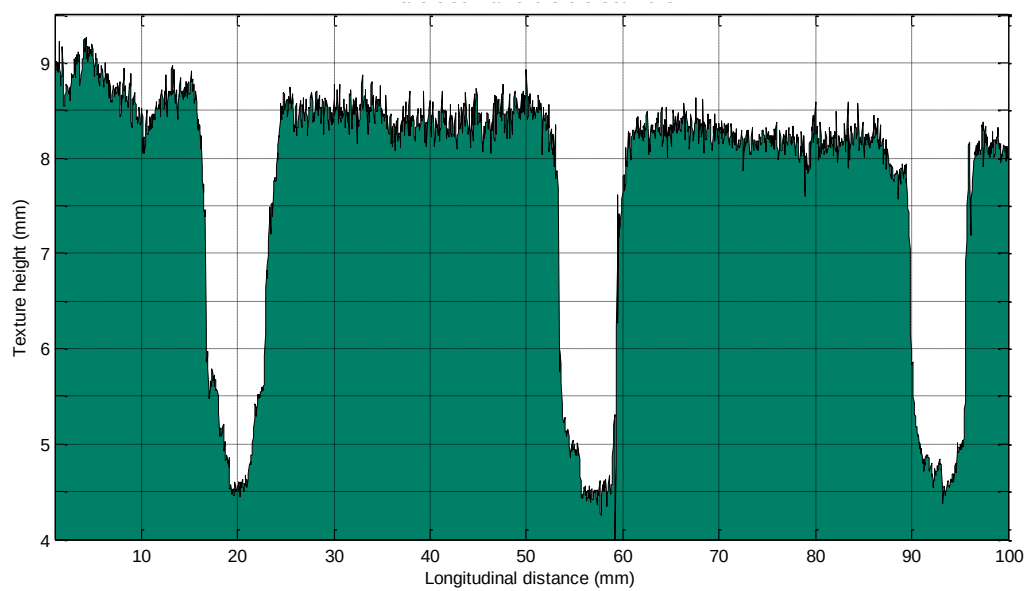


Figure 6.2: Longitudinal profile showing transverse diamond groove.

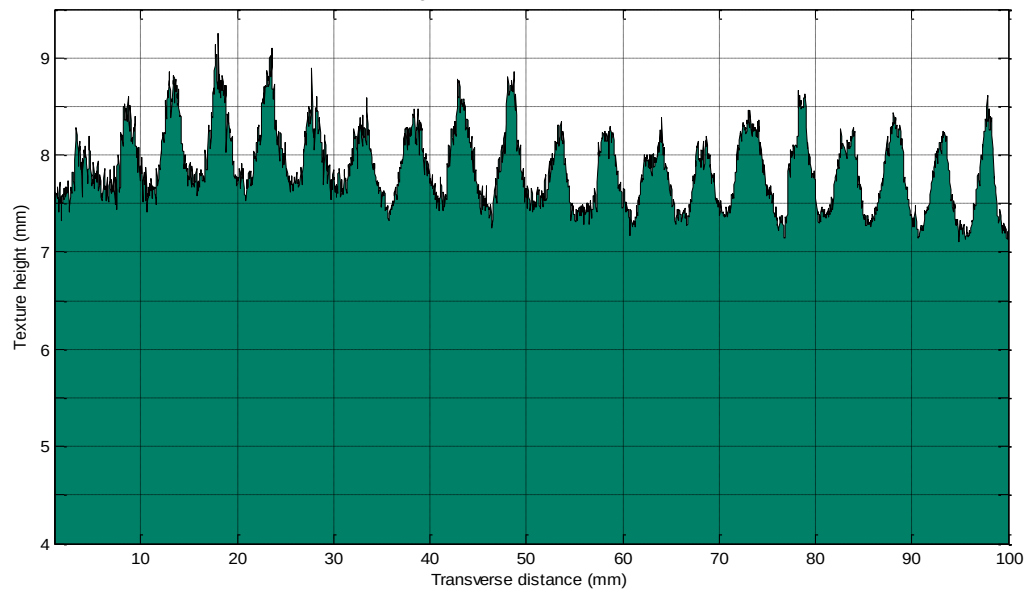


Figure 6.3: Transverse profile showing longitudinal diamond grind.

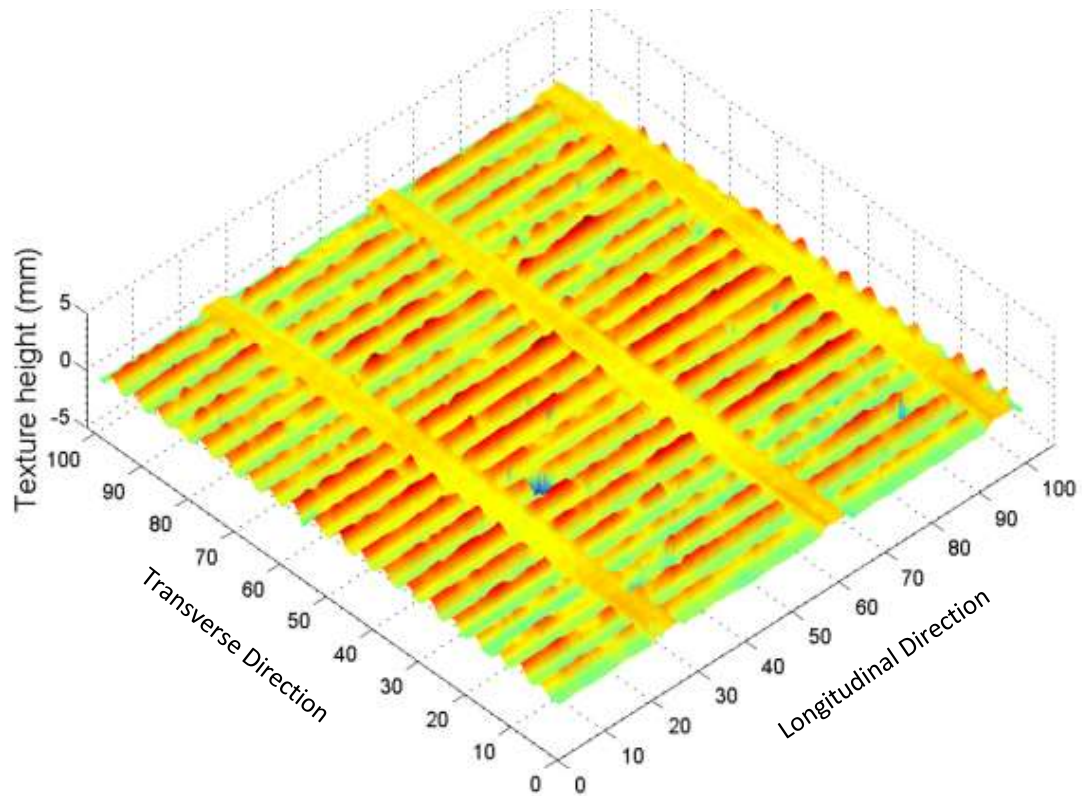


Figure 6.4: Recovered 3D texture height map with transverse diamond groove and longitudinal diamond grind.

6.3 3D Texture Parameters and Regression Analysis with Pavement Friction

Four texture amplitude related macrotexture parameters, simulated mean texture depth (SMTD), root mean square deviation (S_q), Skewness (S_{sk}), and Kurtosis (S_{ku}) were calculated from texture heights after the discrete wavelet transform (DWT) as discussed in section 3.2. These macrotexture parameters are based on the first, second, third, and fourth moment (power) of the macrotexture heights after DWT analysis from the line-laser scanner.

Six volume related macrotexture parameters, peak material volume (V_{mp}), core material volume (V_{mc}), core void volume (V_{vc}), valley void volume (V_{vv}), and the texture height corresponding to 10% and 80% material ratio of the bearing area curve were calculated from texture heights after the discrete wavelet transform (DWT) as discussed in section 3.2.

One index of microtexture, normalized power spectral energy ($NPSE, mm^2/mm^2$) was calculated based on the detailed texture height maps after the discrete wavelet transform (DWT) as discussed in section 3.2.

The 3D texture parameters and their calculation formulas were discussed in section 3.3. The 3D texture parameters in this study are shown in Table 6.1.

6.3.1 Macrotexture Parameters and Pavement Friction

As can be seen from Figure 6.5, the relationship between pavement friction number (FN) and simulated mean macrotexture depth (SMTD) is explored and plotted. The statistical parameters of the regression model between FN and SMTD is shown in Table 6.2.

Figure 6.6 shows the relationship between FN and V_{vc} . The statistical parameters of the regression model between FN and V_{vc} is shown in Table 6.3.

Table 6.1: 3D texture parameters of the tested runway.

Station	SMTD	S_q	S_{sk}	S_{ku}	V_{mp}	V_{mc}	V_{vc}	V_{vv}	H_{10}	H_{80}	NPSE	FN	Type
5+250-3R	0.77	0.28	-0.57	4.09	9.90	236.76	315.87	36.34	0.35	-0.22	0.0959	79.5	AC
5+250-6R	1.22	0.32	-1.09	7.81	11.28	237.39	322.57	47.67	0.37	-0.21	0.1117	87	AC
5+250-3L	0.98	0.32	-0.64	4.41	12.33	255.42	337.71	42.41	0.38	-0.23	0.0743	82	AC
5+250-6L	1.20	0.41	-1.19	7.48	13.20	316.41	408.30	61.15	0.47	-0.28	0.0785	84	AC
6+150-3R	1.43	0.34	0.54	3.10	17.11	284.63	446.50	25.46	0.48	-0.27	0.0786	82.5	AC
6+150-6R	1.49	0.35	0.02	3.50	14.28	279.10	452.04	33.66	0.47	-0.29	0.0603	93	AC
6+150-3L	1.35	0.34	0.50	2.78	15.72	297.28	460.79	22.02	0.48	-0.30	0.0431	90.5	AC
6+150-6L	1.88	0.36	0.16	3.60	15.37	319.58	485.37	25.93	0.50	-0.33	0.0445	98	AC
5+480-3R	0.68	0.20	-1.35	8.20	7.34	153.22	188.72	30.59	0.22	-0.13	0.1197	76	AC
5+480-6R	1.00	0.36	-0.59	4.01	12.99	299.00	392.07	50.69	0.45	-0.27	0.1075	80	AC
5+480-3L	1.18	0.40	-1.44	7.09	10.76	296.77	347.71	69.09	0.42	-0.24	0.1270	76.5	AC
5+480-6L	1.58	0.55	-1.32	6.13	15.33	406.30	495.67	92.14	0.59	-0.34	0.1193	82	AC
5+540-3R	0.97	0.31	-0.86	5.04	10.79	244.70	309.56	46.36	0.36	-0.21	0.1202	74	AC
5+540-6R	0.89	0.31	-0.73	4.51	10.11	249.11	321.29	43.60	0.37	-0.22	0.1125	87	AC
5+540-3L	1.57	0.55	-1.65	9.09	22.26	367.57	471.32	90.69	0.56	-0.30	0.1195	69	AC
5+540-6L	1.48	0.58	-0.60	3.67	19.97	486.12	606.09	80.46	0.69	-0.43	0.0938	75	AC
5+834-3L	2.24	0.35	0.46	3.03	16.71	314.01	465.14	21.21	0.50	-0.31	0.0512	85	PCC
5+834-6L	1.87	0.36	0.52	2.86	16.43	315.32	497.17	20.76	0.51	-0.32	0.0622	93	PCC
5+834-3R	1.51	0.36	-0.03	5.40	19.35	281.73	435.19	36.17	0.48	-0.26	0.0609	85.5	PCC
5+834-6R	1.31	0.35	0.40	2.53	14.81	309.90	476.65	20.14	0.49	-0.32	0.0683	99	PCC
5+965-3L	1.47	0.36	0.39	2.70	16.95	315.09	477.70	25.40	0.50	-0.31	0.0605	91	PCC
5+965-6L	0.90	0.33	-0.02	2.74	12.28	309.91	416.49	24.95	0.45	-0.30	0.0738	91	PCC
5+965-3R	1.54	0.37	0.04	6.52	16.90	300.26	490.15	29.45	0.51	-0.30	0.0583	82	PCC
5+965-6R	1.46	0.39	0.50	2.62	17.12	352.87	521.05	23.69	0.56	-0.34	0.0396	98	PCC
7+076-3R	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	PCC
7+076-6R	0.64	0.23	-1.24	8.59	7.50	169.21	225.08	31.24	0.26	-0.15	0.0818	65	PCC
7+076-3L	0.44	0.13	-1.85	14.44	5.63	92.81	115.93	21.06	0.14	-0.08	0.0781	43	PCC
7+076-6L	0.43	0.12	-0.25	3.59	5.22	105.36	142.40	13.76	0.16	-0.10	0.0654	51	PCC
7+183-3L	0.80	0.14	-1.70	28.00	8.01	91.46	134.08	16.41	0.15	-0.08	0.1134	29	PCC
7+183-6L	2.14	0.34	-2.59	29.54	18.59	203.38	263.61	51.79	0.31	-0.17	0.0655	52	PCC
7+183-3R	1.62	0.23	-1.40	17.39	15.00	133.53	174.65	35.72	0.20	-0.12	0.1222	62	PCC
7+183-6R	1.17	0.15	-0.74	17.31	8.39	108.13	151.41	19.02	0.17	-0.10	0.0919	77	PCC

Where

SMTD=simulated mean texture depth (mm)

 S_q = Root mean square deviation (mm) S_{sk} =Skewness of texture height map S_{ku} =Kurtosis of texture height map V_{mp} =Peak material volume (ml/m^2) V_{mc} =Core material volume (ml/m^2) V_{vc} =Core void volume (ml/m^2) V_{vv} =Valley material volume (ml/m^2) H_{10} (H_{80}) =Texture height corresponding to 10% (80%) material ratio of the bearing area curve (mm)NPSE=Normalized power spectral energy (mm^2/mm^2)

FN=Friction number

Type=The type of the pavement mixture

N/A= Not available. The raw data file was corrupted.

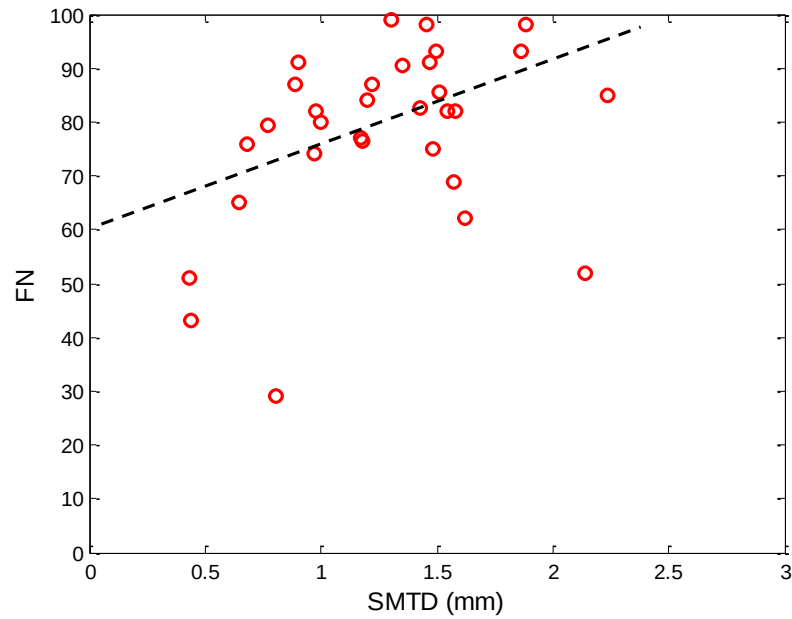


Figure 6.5: Relationship between FN and SMTD.

Table 6.2: FN and SMTD regression model and hypothesis test at 95% confidence level.

Regression model $FN = \alpha + \beta \times SMTD$					
Coefficient	Estimate	Standard error	t-Statistic	t-Critical	p-Value (<0.05)
α	60.51	8.3138	7.2784	2.0452	5.1388×10^{-14}
β	13.87	6.195	2.2381	2.0452	0.033061
Regression model $FN = 60.51 + 13.87 SMTD$					
Number of observations	31				
Root mean squared error	15.5				
R^2	0.147				
F-Statistic	16.67				
F-Critical	3.3277				
p-Value (<0.05)	0.0331				

The V_{vc} is an index to represent the core void of surface. It represents the water/air retention/drainage properties of the pavement surface. The R^2 value of 0.545 indicates that the V_{vc} is remarkable to the pavement friction. There is no other document available to quantify the relationship between pavement friction and volume texture parameters although researchers have mentioned the concepts and their potential application (Rasmussen et al., 2011a).

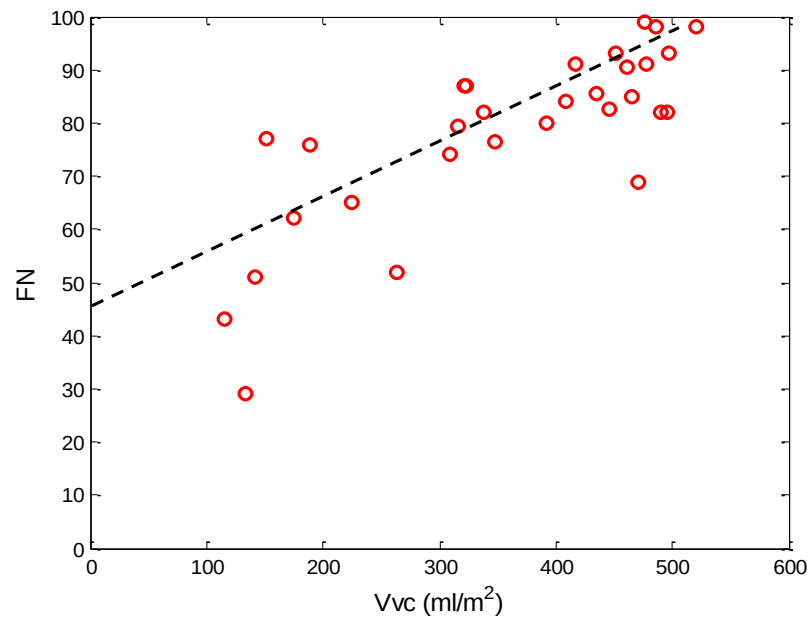


Figure 6.6: Relationship between FN and V_{vc} .

Table 6.3: FN and V_{vc} regression model and hypothesis test at 95% confidence level.

Regression model	$FN = \alpha + \beta \times V_{vc}$				
Coefficient	Estimate	Standard error	t-Statistic	t-Critical	p-Value (<0.05)
α	45.049	5.9583	7.5608	2.0452	2.4642×10^{-8}
β	0.0901	0.0153	5.8906	2.0452	2.1515×10^{-6}
Regression model	$FN = 45.05 + 0.09 V_{vc}$				
Number of observations	31				
Root mean squared error	11.3				
R^2	0.545				
F-Statistic	115.47				
F-Critical	3.3277				
p-Value (<0.05)	2.15×10^{-6}				

Regression and statistical analysis between FN and other macrotexture indices are also investigated as presented in Table 6.4. In general, a certain trend could be found between FN and a single macrotexture parameter. However the coefficient of determination (R^2) was not high ranging between 0.147 to 0.545 although both t-test and F-test showed that the regression models coefficients are significant at the 5% significance level.

Table 6.4: Summary of regression analysis between FN and single macrotexture index.

Regression model	Coefficient of determination (R^2)	F-statistic vs. constant model
$FN=60.51+13.87 SMTD$	0.15	5.01
$FN=56.52+1.60 V_{mp}$	0.18	6.35
$FN=48.08+0.11 V_{mc}$	0.42	21.04
$FN=45.05+0.09 V_{vc}$	0.55	34.7
$FN=46.05+79.02 Height10$	0.48	26.6

The relationship between pavement friction and various combinations of two macrotexture parameters are also explored.

The predicted friction number FN is shown in Equation (6.1) if both *SMTD* and kurtosis (S_{ku}) are included.

$$\begin{aligned}
 FN &= 73.77 + 14.08 SMTD - 1.81 S_{ku} \\
 R^2 &= 0.73
 \end{aligned}
 \tag{6.1}$$

Where

FN = predicted pavement friction,

$SMTD$ = simulated mean texture depth,

S_{ku} = kurtosis of surface macrotexture,

R^2 = coefficient of determination.

As can be seen from Equation (6.1), the prediction of FN was improved than that shown in Figure 6.5. In addition to *SMTD*, the texture distribution shape represented by kurtosis (S_{ku}) of the texture is significant to the friction values. The more flatted distribution of the surface texture is helpful to pavement friction. This observation echos the findings

in section 4.3.4.

Table 6.5 presents the coefficients and statistical parameters of the regression model. A significant relationship ($R^2 = 0.73$) was found among pavement friction, SMTD, and kurtosis (S_{ku}) of the texture. As can be seen from Table 6.5, the t-test, F-test, and p-values show the coefficients and regression model are significant at 95% confidence level. The statistical analysis indicates that the linear regression model is significant and can be used to predict pavement friction values.

Table 6.5: Regression model and hypothesis test at 95% confidence level.

Regression model		$FN = \alpha + \beta_1 \times SMTD + \beta_2 \times S_{ku}$			
Coefficient	Estimate	Standard error	t-Statistic	t-Critical	p-Value (<0.05)
α	73.773	5.0535	14.598	2.0452	1.284×10^{-14}
β_1	14.081	3.5452	3.9719	2.0452	4.531×10^{-4}
β_2	-1.8107	0.2327	-7.7819	2.0452	1.176×10^{-8}
Regression model		$FN = 73.77 + 14.08SMTD - 1.81 S_{ku}$			
Number of observations		31			
Root mean squared error		8.85			
R^2		0.73			
F-Statistic		37.9			
F-Critical		3.3277			
p-Value (<0.05)		31.07×10^{-8}			

6.3.2 Microtexture Parameters and Pavement Friction

The predicted friction number FN is shown in Equation (6.2) if $SMTD$, S_{ku} , and $NPSE$ are included. The prediction of FN is hardly improved comparing to the regression model as shown in Equation (6.1).

$$\begin{aligned}
 FN &= 74.97 + 13.84SMTD - 1.79S_{ku} - 0.12NPSE \\
 R^2 &= 0.731
 \end{aligned}
 \tag{6.2}$$

Where

- FN = predicted pavement friction,
 $SMTD$ = simulated mean texture depth,
 S_{ku} = kurtosis of of surface macrotexture,
 $NPSE$ = normalized power spectral energy for microtexture,
 R^2 = coefficient of determination.

These observations indicate that the proposed microtexture index, NPSE, is not a significant factor to the pavement friction. Possible reasons are as follows:

- Pavement friction was measured at 65 km/h, while the surface texture was obtained by stationary measurement. The PIARC (1995) program found that macrotexture contributes more than 95% of pavement friction at speeds above 105km/h.
- FN was measured with self-watering conditions at 0.5mm water film depth which possibly eliminate/mitigate the impact of microtexture, while texture measurement was conducted on dry condition.
- The friction in this research was measured by using a smooth ASTM test tire which is more sensitive to macrotexture than to microtexture (Hall et al., 2009b)

More tests and analysis are needed to recover pavement surface microtexture or explore its contribution to pavement friction. The proposed microtexture index, NPSE, need to be investigated more as well.

6.4 Findings and Recommendations

The relationship between pavement friction and various single macrotexture parameter were explored. A linear relationship, with an R^2 value ranging from 0.147 to 0.545 was found between pavement friction and various single macrotexture index. It is found that a single macrotexture is not adequate to predict pavement friction.

No significant relationship is found between the proposed microtexture index, NPSE, and pavement friction. More measurements or analysis is needed to explore the impact of microtexture to pavement friction.

A regression model with an R^2 value of 0.73 was found among FN, SMTD, and Kurtosis (S_{ku}) of the surface texture. This finding indicates that in addition to pavement texture depth represented by SMTD, the texture distribution represented by S_{ku} (or S_{sk} as discussed in Chapter 4) is a significant factor to pavement friction. It is recommended to use Equation (6.1) for the prediction of runway pavement friction.

Figure 6.7 is comparing the measured and modeled pavement friction by using Equation (6.1).

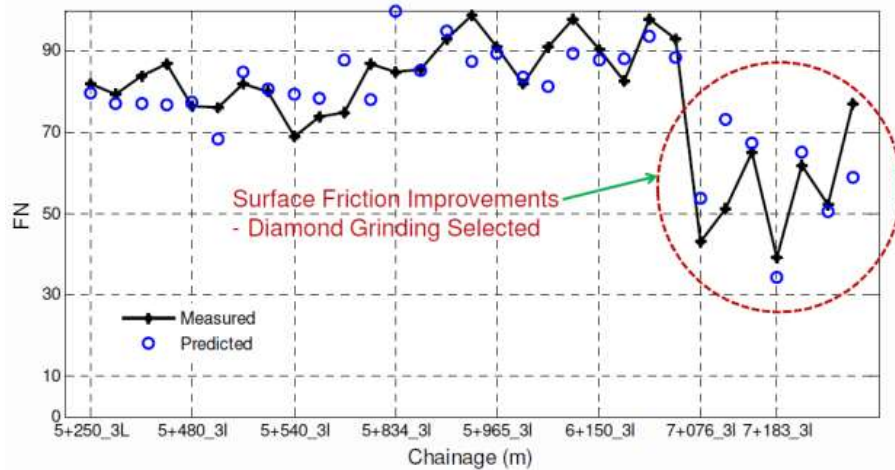


Figure 6.7: Compare field measured FN with modeled values.

As can be seen from Figure 6.7, the friction values are much lower at the landing area start from 6+950. The Winnipeg Airports Authority Inc. decided to carry out runway surface friction improvements by diamond grinding for the landing area at the beginning of October 2013. Texture was measured again by using line-laser scanner immediately after the surface friction improvement. The predicted friction values are shown in Figure 6.8.

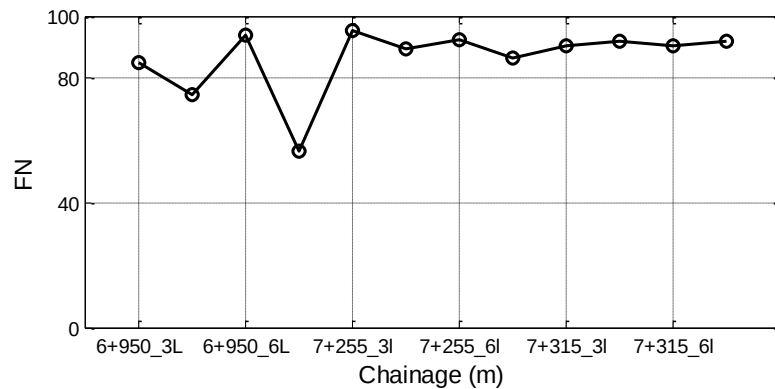


Figure 6.8: Predicted friction values after diamond grinding for landing area.

Figure 6.9 is comparing the runway friction values before and after diamond grinding for landing area. It can be concluded that the diamond grinding for landing area has improved significantly the runway friction values for landing area, and that the predicted F_n s for landing area after the diamond grinding match the friction values for other area of the runway.

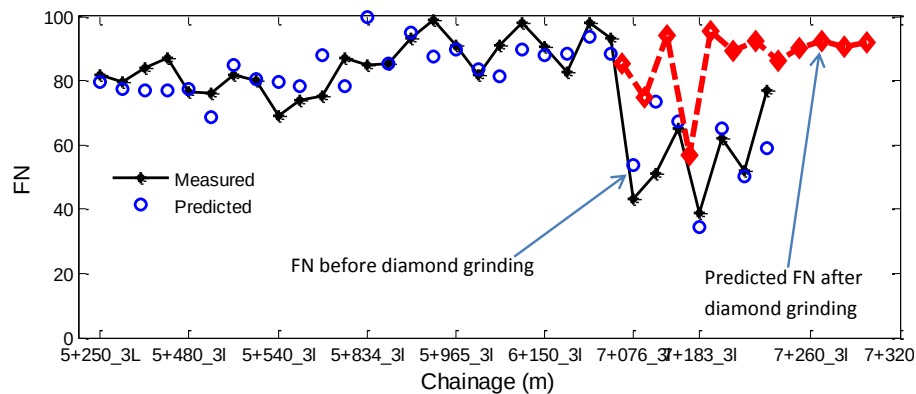


Figure 6.9: A comparison of F_n s before and after diamond grinding for landing area.

It is recommended that James Armstrong Richardson International Airport (Winnipeg) Authority considers using texture measurements as backup for friction data, and to investigate localized polished areas for which friction testing has not been arranged.

Chapter 7

EVALUATING THE IMPACTS OF RECLAIMED ASPHALT PAVEMENT AND RECYCLED ASPHALT SHINGLES ON SURFACE TEXTURE

7.1 Introduction

Use of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) in asphalt pavement is generally accepted and extensively used in asphalt pavement construction. Numerous studies (Shu et al., 2008, McDaniel et al., 2012, Mogawer et al., 2012) found that dynamic modulus, resilient modulus and indirect tensile test usually increase by increasing RAP or RAS. Increase in RAP or RAS content results in increase in stiffness of the asphalt mixture due to the influence of aged binder. Other studies (McDaniel et al., 2000, Silva et al., 2012, Karlsson¹ and Isacsson, 2006) showed that an asphalt mixture resistance to rutting improves especially at intermediate and high temperature as amount of RAP increases in hot mix asphalt (HMA).

The type, shape, and gradation of aggregate have significant influence upon surface texture and its durability. The properties of RAP/RAS are different from virgin aggregate. Kowalski et al. (2010) investigated the influence of RAP on pavement surface friction by evaluating the polishing properties of laboratory specimens. Previous research (Kowalski et al., 2010) found that the presence of RAP/RAS influenced negatively the pavement surface terminal friction value and surface polishing rate. However, to the author's knowledge, there has been no prior publication on the evaluation of the impacts of RAP or RAS on pavement surface texture.

This research he proposes a methodology and new 3D texture parameters as discussed in Chapter 3 to analyze the effect of mix design on pavement texture and in turn the

friction and noise.

The objective of this research is to assess the impact of RAP/RAS on pavement surface texture under various environmental or loading conditions. This study was carried out on two scenarios as follows:

- Pavement sections with RAP content of 0% , 15% , and 50%. The sections have been in service for five years at the time of testing.
- Pavement sections with RAP content of 10% and RAS content of 0% or 3%. These pavement sections have been in service for two years at the time of testing.

7.2 Assessing Surface Texture of Pavements with Various Contents of RAP

In this research, pavement texture was measured by using a portable line-laser scanner to recover the surface texture in three-dimensional (3D) manner. The recovered 3D texture heights were decomposed into four levels by using discrete wavelet transform to separated macrotexture from microtexture. 3D texture indices were calculated and analyzed for the tested pavement sections including various percentages of RAP.

The test sections were part of a study of the effect of high RAP percentage on pavement performance (Hajj et al., 2011). The mixtures contained 0% , 15% , and 50% RAP. Three of the mixtures used an asphalt binder with PG 58-28 (specified as penetration grade 150-200). One section was constructed with a softer binder PG 52-34 (specified as penetration grade 200-300) to alleviate the effect of aged RAP binder.

The tested pavement sections were constructed in September 2009 on provincial trunk highway (PTH) 8 between Gimli and Hnausa in Manitoba, Canada. The pavement consisted of two 5 centimetres lifts with conventional HMA and various percentages of RAP as shown in Table 7.1. The aggregate gradations are shown in Figure 7.1. The traffic

information of the pavement was provided by Manitoba Infrastructure and Transportation and is shown in Table 7.2.

Strict quality control measures were in place during the construction of these sections. The same hot plant, truck type, paver, crews, and compaction equipment were employed. Identical compaction effort was applied to the test sections (Hajj et al., 2011).

Table 7.1: Tested pavements with various percentages of RAP and different binder.

Section	Reclaimed asphalt pavement (RAP) content (%)	Virgin asphalt binder used	
		Penetration grade	(Equivalent) Performance grade
0%RAP150	0	Pen 150-200	PG 58-28
15%RAP150	15	Pen 150-200	PG 58-28
50%RAP150	50	Pen 150-200	PG 58-28
50%RAP200	50	Pen 200-300	PG 58-34

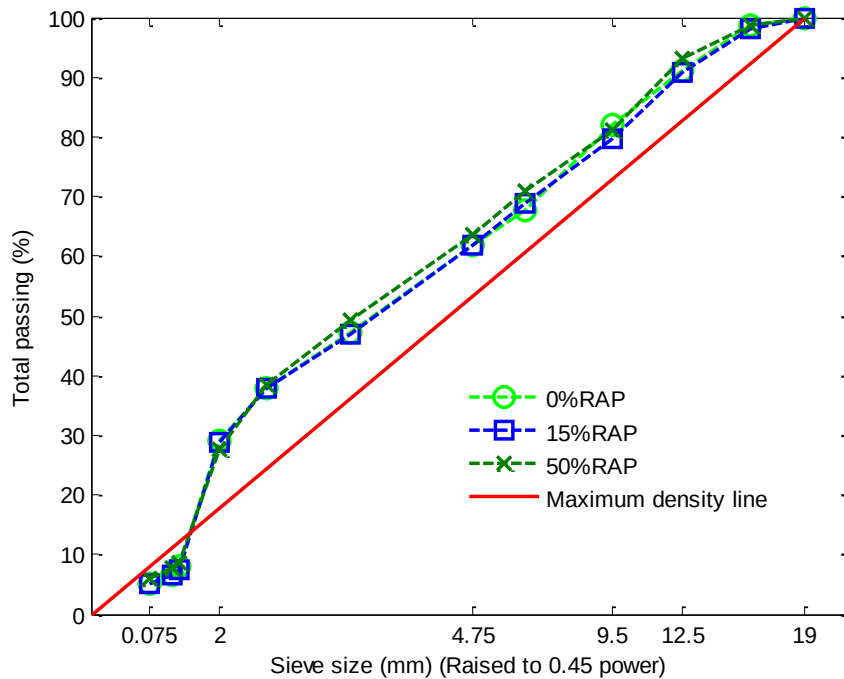


Figure 7.1: Aggregate gradation of tested sections.

Table 7.2: Traffic information of tested pavement sections (Hajj et al., 2011).

Item	Value
Two-Directional average daily traffic	25,395
Truck percent of ADT, %	7.6
Two-Directional average daily truck traffic	1,930
Directional split, %	50/50
Annual growth rate, %	2.0
Annual one-directional design equivalent single axle load	80,000
20 year one-directional design ESAL	1,950,00

7.2.1 Texture Analysis and Discussions

Ten replicate measurements were conducted on the outer wheel-path of tested pavement sections. The texture parameters of the 10 replicate measurements of each section are presented in Table 7.3 and Table 7.4.

To determine whether the means of the calculated 3D texture of the four tested sections are statistically equal or not, the analysis of variance (ANOVA) was carried out.

The purpose of one-way ANOVA is to find out whether data from the four sections have a common mean to determine whether the sections are actually different in the calculated 3D texture parameters.

One-way ANOVA is a special case of the linear model which assumes that each texture parameter is a constant plus a random disturbance. The objective of ANOVA is to check if the constants are all the same, or in other words, there is no significant difference among the sections (mixes).

If the one-way ANOVA shows there is a significant difference in means among the sections, multiple comparisons between all pair-wise means are conducted to determine how they differ from one another.

Figure 7.2 shows the *SMTD* and its ANOVA result for the tested sections. As can be seen from Figure 7.2, the mean values of *SMTD* of the two sections with low

Table 7.3: Texture parameters of tested sections.

Measurement		SMTD	S_q	S_{sk}	S_{ku}	V_{mp}	V_{mc}	V_{vc}	V_{vv}	H_{10}	H_{80}	NPSE
50%RAP200	1	0.98	0.29	0.07	4.24	14.4	232.9	379.7	28.9	0.41	-0.22	0.0757
	1*	0.98	0.29	0.07	4.24	14.4	232.9	379.7	28.9	0.41	-0.22	0.0757
	2	1.01	0.30	0.21	3.54	15.4	240.5	385.6	29.9	0.42	-0.23	0.0751
	3	1.25	0.36	-0.36	5.38	15.1	280.3	434.4	41.3	0.48	-0.26	0.0726
	3*	1.25	0.36	-0.36	5.38	15.1	280.3	434.4	41.3	0.48	-0.26	0.0726
	4	1.04	0.33	-0.17	3.84	12.4	270.0	415.4	36.0	0.46	-0.25	0.0615
	5	1.07	0.31	0.02	3.67	13.8	249.4	392.4	32.4	0.43	-0.23	0.0597
	5*	1.07	0.31	0.02	3.67	13.8	249.4	392.4	32.4	0.43	-0.23	0.0597
	6	1.03	0.33	-0.06	4.03	13.9	259.1	421.4	33.9	0.46	-0.25	0.0584
	7	1.24	0.35	-0.07	3.69	16.4	283.1	441.8	40.0	0.48	-0.27	0.0596
	Ave	1.09	0.32	-0.06	4.17	14.5	257.8	407.7	34.5	0.44	-0.24	0.0671
	Std	0.11	0.03	0.19	0.68	1.1	19.7	24.4	4.9	0.03	0.02	0.0078
50%RAP150	1	0.92	0.31	-0.44	5.06	13.16	246.61	371.89	36.35	0.41	-0.23	0.0589
	2	0.84	0.30	-0.56	5.73	11.80	239.68	366.04	34.60	0.40	-0.22	0.0550
	3	1.23	0.35	-0.17	4.60	15.61	270.57	432.59	38.13	0.47	-0.25	0.0764
	4	1.11	0.33	-0.08	3.93	14.68	263.09	410.92	34.91	0.45	-0.25	0.0622
	5	0.97	0.32	-0.26	4.36	13.81	258.33	397.24	36.15	0.44	-0.24	0.0583
	6	0.99	0.28	0.02	4.03	15.28	220.27	329.95	30.10	0.36	-0.21	0.0652
	7	1.08	0.35	-1.13	12.45	14.45	261.86	412.73	41.62	0.46	-0.24	0.0713
	8	1.38	0.36	-0.36	4.89	14.36	284.96	444.04	42.39	0.49	-0.26	0.0723
	9	1.02	0.32	-0.33	4.33	12.93	252.29	378.81	37.31	0.42	-0.23	0.0685
	10	1.18	0.34	-0.26	4.20	13.71	275.15	420.05	40.01	0.46	-0.25	0.0723
	Ave	1.07	0.33	-0.36	5.36	14.0	257.3	396.4	37.2	0.44	-0.24	0.0660
	Std	0.16	0.03	0.32	2.55	1.1	18.7	34.7	3.6	0.04	0.02	0.0072

Where

Ave = Averaged value of the 10 replicate measurements

Std = Standard deviation

SMTD = simulated mean texture depth (mm)

S_q = Root mean square deviation (mm)

S_{sk} = Skewness of texture height map

S_{ku} = Kurtosis of texture height map

V_{mp} = Peak material volume (ml/m^2)

V_{mc} = Core material volume (ml/m^2)

V_{vc} = Core void volume (ml/m^2)

V_{vv} = Valley material volume (ml/m^2)

H_{10} (H_{80}) = Texture height corresponding to 10% (80%) material ratio of the bearing area curve (mm)

NPSE = Normalized power spectral energy (mm^2/mm^2)

* These data are duplicates of the data from the rows above correspondingly for the purpose of analysis of variance (ANOVA). There were 7 measurements at section of 50%RAP200. By adding 3 duplicates, make it 10 measurements the same as other sections.

Table 7.4: Texture parameters of tested sections (Cont'd from Table 7.3).

Measurement		SMTD	S_q	S_{sk}	S_{ku}	V_{mp}	V_{mc}	V_{vc}	V_{vv}	H_{10}	H_{80}	NPSE
15%RAP150	1	0.90	0.29	-0.57	8.10	12.17	215.40	356.07	31.21	0.39	-0.20	0.0695
	2	0.95	0.25	0.21	3.71	13.02	200.63	334.82	23.78	0.36	-0.20	0.0737
	3	0.85	0.25	0.19	3.66	12.87	197.46	319.12	24.71	0.34	-0.19	0.0733
	4	0.87	0.26	0.13	4.37	13.57	204.87	341.55	24.56	0.37	-0.20	0.0533
	5	0.92	0.26	-0.37	7.12	11.92	200.29	325.50	25.71	0.35	-0.19	0.0618
	6	0.84	0.27	0.11	3.84	13.32	212.21	351.09	27.34	0.38	-0.20	0.0756
	7	0.77	0.26	-0.31	4.59	10.27	205.58	316.10	29.82	0.35	-0.19	0.0639
	8	0.89	0.29	-0.22	4.49	11.32	224.60	364.81	30.47	0.40	-0.21	0.0539
	9	0.86	0.25	0.05	3.94	11.11	200.24	327.10	23.65	0.35	-0.19	0.0551
	10	1.04	0.31	-0.07	4.36	14.99	236.25	388.09	33.71	0.42	-0.22	0.0501
	Ave	0.89	0.27	-0.08	4.82	12.5	209.8	342.4	27.5	0.37	-0.20	0.0630
	Std	0.07	0.02	0.27	1.53	1.4	12.5	22.8	3.6	0.03	0.01	0.0096
0%RAP150	1	0.95	0.25	-0.14	4.50	12.47	195.91	306.82	27.43	0.33	-0.18	0.0760
	2	0.84	0.23	0.35	3.70	13.56	184.09	297.90	20.65	0.32	-0.18	0.0598
	3	0.77	0.25	-0.05	4.23	11.78	195.66	311.93	25.88	0.34	-0.19	0.0618
	4	0.81	0.24	-0.10	4.30	10.77	191.05	303.51	25.77	0.33	-0.18	0.0593
	5	0.72	0.23	0.08	4.00	11.99	177.26	289.54	23.93	0.31	-0.17	0.0629
	6	0.93	0.23	0.04	4.02	10.48	186.29	302.74	23.54	0.33	-0.18	0.0691
	7	0.78	0.25	0.18	3.45	11.20	198.80	330.44	24.98	0.36	-0.19	0.0615
	8	0.68	0.22	0.06	3.49	9.87	184.27	288.67	21.89	0.31	-0.17	0.0581
	9	0.78	0.22	-0.83	7.79	9.34	166.66	253.09	28.61	0.28	-0.15	0.0528
	10	0.81	0.24	0.05	4.12	12.86	192.81	306.00	25.27	0.33	-0.19	0.0493
	Ave	0.81	0.24	-0.04	4.36	11.4	187.3	299.1	24.8	0.33	-0.18	0.0611
	Std	0.08	0.01	0.31	1.25	1.3	9.8	20.0	2.4	0.02	0.01	0.0076

Where

Ave = Averaged value of the 10 replicate measurements

Std = Standard deviation

SMTD = simulated mean texture depth (mm)

 S_q = Root mean square deviation (mm) S_{sk} = Skewness of texture height map S_{ku} = Kurtosis of texture height map V_{mp} = Peak material volume (ml/m²) V_{mc} = Core material volume (ml/m²) V_{vc} = Core void volume (ml/m²) V_{vv} = Valley material volume (ml/m²) H_{10} (H_{80}) = Texture height corresponding to 10% (80%) material ratio of the bearing area curve (mm)NPSE = Normalized power spectral energy (mm²/mm²)

RAP contents (0%*RAP*150 and 15%*RAP*150) are significantly different from those of high RAP contents (50%*RAP*150 and 50%*RAP*200) at a confidence level of 95%. It was also found that there is no significant difference between the SMTDs of the two low RAP sections or the two high RAP sections as can be seen from Figure 7.2 (a). The SMTDs of the four sections were box-plotted as shown in Figure 7.2 (b). The central mark is the median, the edges of the box are 25th and 75th percentiles. The outliers were plotted individually.

Researchers found that factors affecting pavement macrotexture are maximum aggregate dimensions, coarse aggregate types, fine aggregate types, mix gradation, mix air void, and mix binder (Henry, 2000, Hall et al., 2009b, PIARC, 1995, AASHTO, 1976). Since the gradations of all the four mixtures of the sections are almost identical as can be seen in Figure 7.1, and the binders for sections of 0%*RAP*150, 15%*RAP*150, 50%*RAP*150 are identical. The only difference among 0%*RAP*150, 15%*RAP*150, and 50%*RAP*150 is the RAP content. As can be seen from Figure 7.2, higher percentage of RAP content increased SMTD. In summary, the presence of RAP in these pavement sections resulted in higher macrotexture. Studies have found that the amplitude of macrotexture is positively related to pavement friction and thus safety (Henry, 2000, Hall et al., 2009b). In conclusion, the RAP content in this research has improved pavement surface macrotexture. However, the slightly larger standard deviation of SMTD for high RAP content (50%) sections as can be seen from Figure 7.2 (b) implies potentially less control over the surface macrotexture on finished pavement. Comparing 50%*RAP*150 with 50%*RAP*200, the change of binder from Pen 150-200 to Pen 200-300 for the mixes with 50% of RAP did not have a significant impact on pavement SMTD.

The ANOVA results of S_q is shown in Figure 7.3. The S_q of 0%*RAP*150 is significantly different from those of sections with RAP content. No significant difference was found between S_q of the sections of 50%*RAP*150 and 50%*RAP*200.

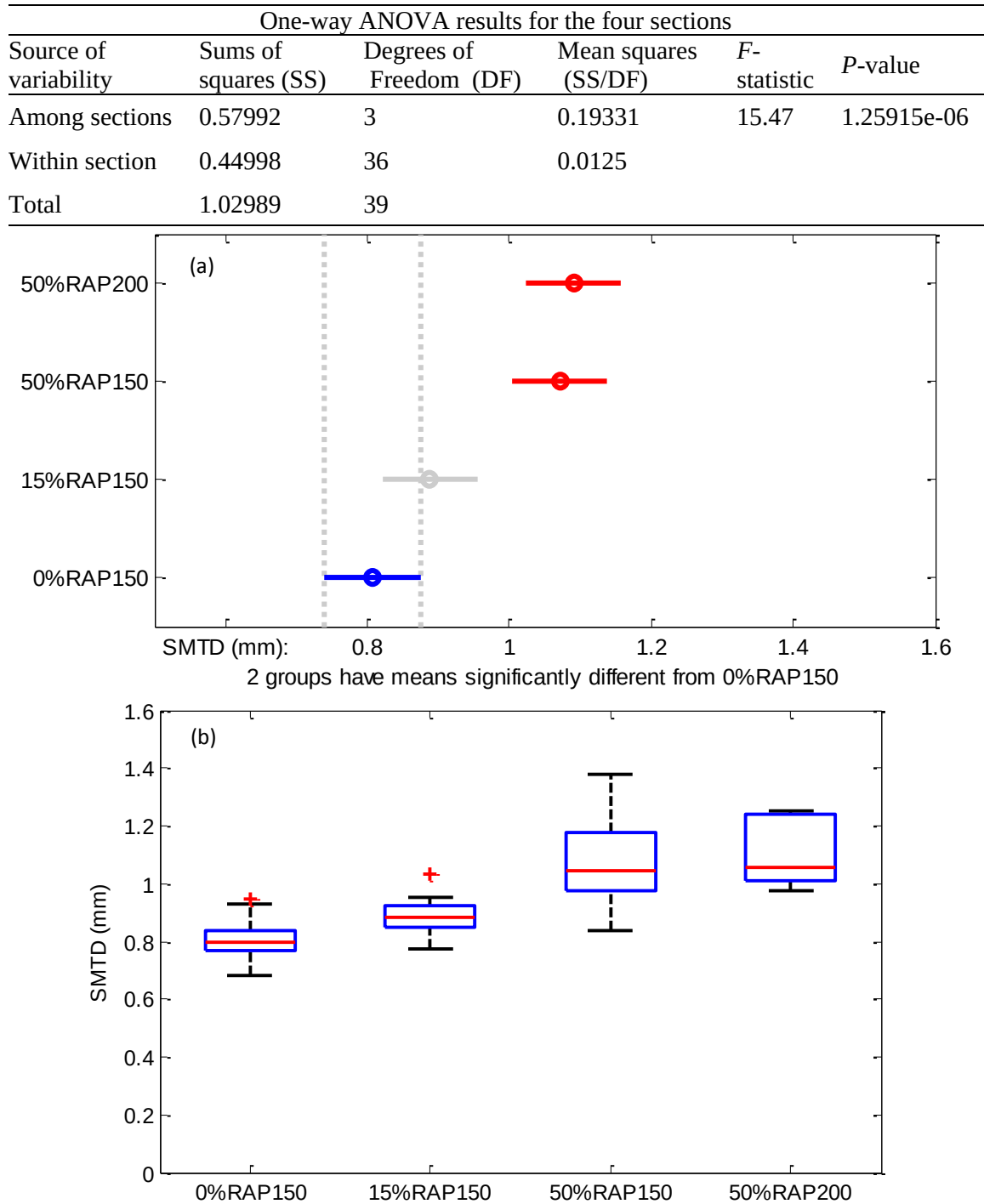


Figure 7.2: ANOVA of *SMTD* : (a) multiple comparison of means, confidence intervals and (b) boxplot of median, 25%/75% quantile.

One-way ANOVA results for the four sections					
Source of variability	Sums of squares (SS)	Degrees of Freedom (DF)	Mean squares (SS/DF)	<i>F</i> -statistic	<i>P</i> -value
Among sections	0.05779	3	0.01926	40.72	1.1621e-11
Within section	0.01703	36	0.00047		
Total	0.07482	39			

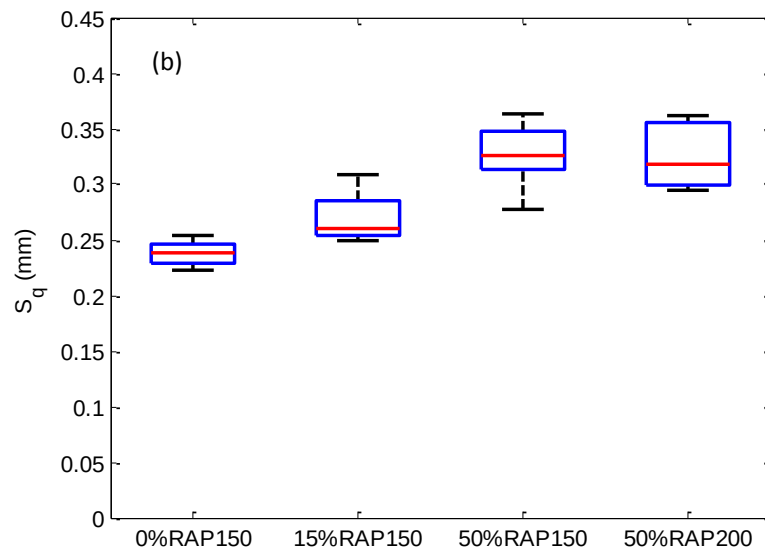
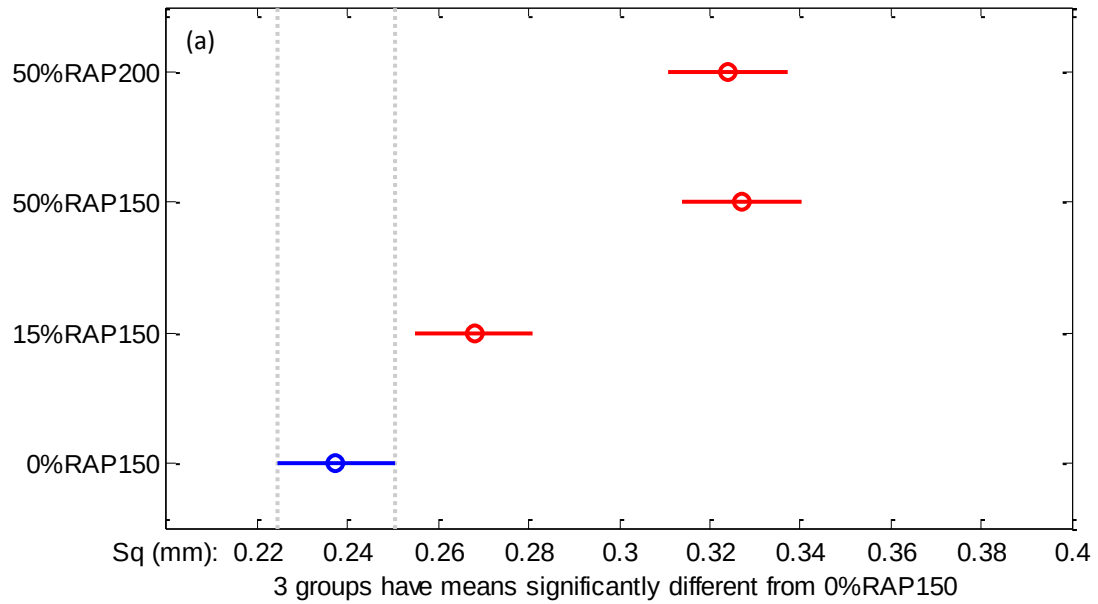


Figure 7.3: ANOVA of S_q : (a) multiple comparison of means, confidence intervals and (b) boxplot of median, 25%/75% quantile.

Figure 7.4 shows S_{ku} of the four tested sections. Kurtosis (S_{ku}) is a measure of the spread of the texture heights distribution. Kurtosis also provides a measure of the spikiness of the surface. A surface with projecting sharp texture will have a high kurtosis value and a flatter surface will have a lower kurtosis value (Davim, J. P. (Ed), 2010). The higher the kurtosis, the more peaked the distribution. Higher kurtosis means more of the variability is due to mainly extreme deviations from the mean, instead of being caused by more but smaller deviations from the mean. The high peak indicates the distribution is more clustered around the mean than in a normal distribution, and the standard deviation will be relatively smaller. A normal distribution has a kurtosis of 3. If a distribution has a kurtosis below 3, it is considered to be flatter than a normal distribution. For example, the kurtosis is 1.8 for a uniform distribution of texture heights. As can be seen from Figure 7.4, no significant difference was found among S_{ku} of the four tested sections.

As shown in Figure 7.4 (a), the kurtosis of the tested sections are all greater than 3, which indicates that the surface is dominated by a few sharp peaks or valleys due to either the method of construction (paving and compaction), voids created by raveling, or environmental loadings to the surface. There is no significant difference of S_{ku} among the tested sections. The S_{ku} of 50%RAP150 is slightly higher than those of 0%RAP150 and 15%RAP150. Comparing the S_{ku} of 50%RAP150 and 50%RAP200, the S_{ku} of 50%RAP200 is closer to the S_{ku} of lower RAP content mixture. This observation implies that the changing of binder from PG 58-28 to PG 58-34 makes texture distribution closer to the virgin or lower RAP content mixture. Or, in other words, the changing of binder is helpful.

Figure 7.5 shows S_{sk} of the four tested sections. Skewness (S_{sk}) is a measure of the lack of symmetry in a statistical distribution. Recommended by ISO 4287 (1997), skewness is used to assess the directionality of the surface texture to differentiate the contribution of positive texture from negative texture. A negative value of skewness indicates that the left

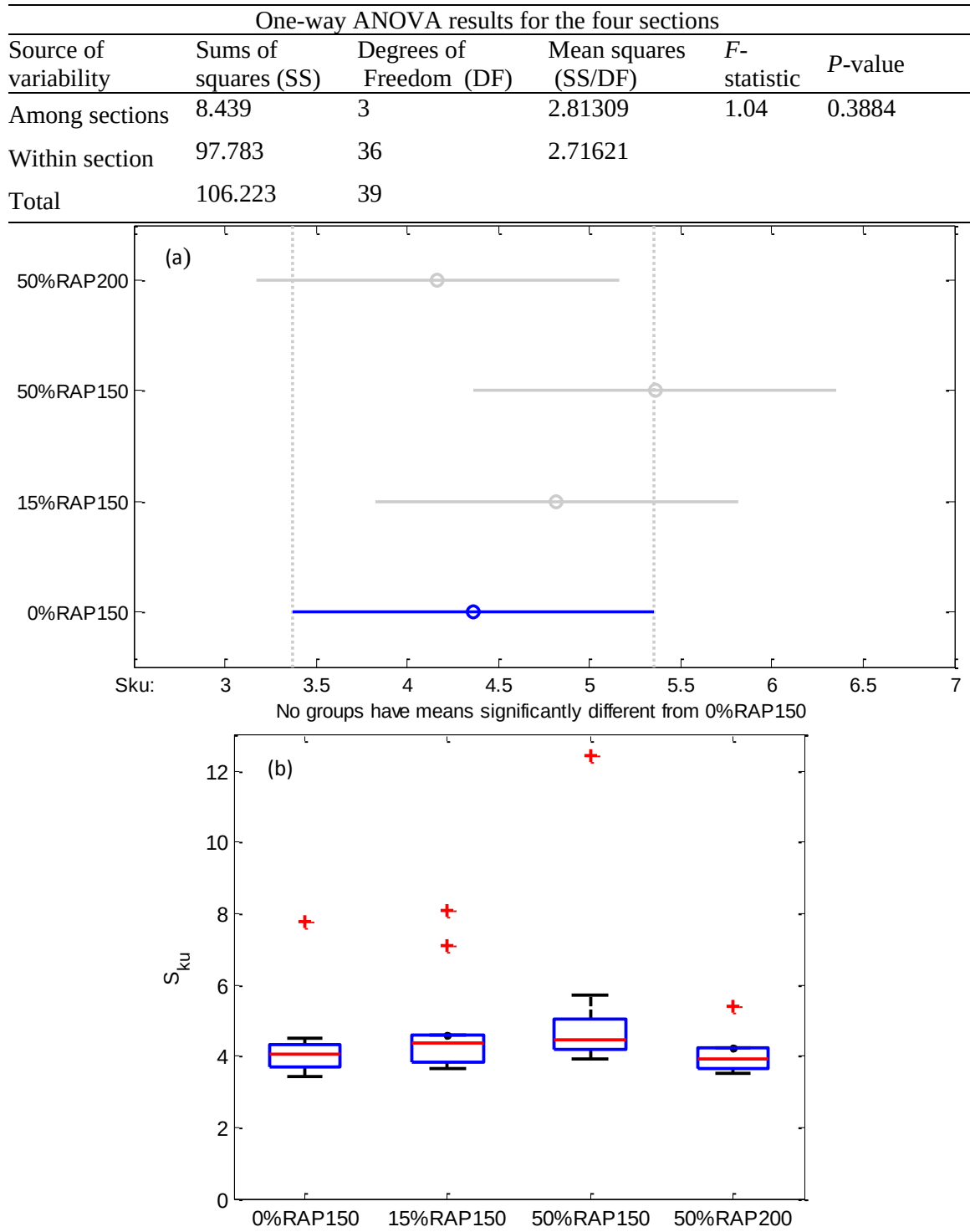


Figure 7.4: ANOVA of S_{ku} : (a) multiple comparison of means, confidence intervals and (b) boxplot of median, 25%/75% quantile.

side of the probability density function is longer than the right side. In other word, more texture smaller than the mean value. As can be seen from Figure 7.5, the S_{sk} of 0%RAP150 and 15%RAP150, and 50%RAP200 are close to zero, which means the texture distribution is or nearly symmetric.

Comparing the sections of 50%RAP150 and 50%RAP200, changing of binder from PG 58-28 to PG 58-34 is helpful in terms of texture distribution represented by S_{sk} although the difference is not statistically different but the F-test is very marginal as can be seen from Figure 7.5. Comparing to 50%RAP200, the more negative S_{sk} of 50%RAP150 may indicate that more positive texture was worn out by traffic, as shown in Figure 7.6, due to the harder asphalt binder. Again, the changing of binder (using softer asphalt binder to mitigate the effect of hardened RAP binder, Hajj et al., 2011) is helpful for the high RAP content sections, but more tests are needed to confirm this observation.

Figure 7.7 shows V_{mp} of the four test sections. The V_{mp} of low RAP content sections (0%RAP150 and 15%RAP150) are significantly different from those of high RAP content sections (50%RAP150 and 50%RAP200). Comparing 50%RAP150 with 50%RAP200, the harder asphalt binder of 50%RAP150 resulted in lower V_{mp} value. This observation implies again more positive texture was lost for 50%RAP150 although is not statistically different. This finding echoes the analysis from S_{sk} evaluation as shown in Figure 7.5.

Figure 7.8 shows V_{mc} of the four test sections. As can be seen from Figure 7.8, the percentage of RAP contents has significant impact of the core volume material values of the pavement texture. The changing binder of 50%RAP150 and 50%RAP200 does not have any significant impact on V_{mc} . Combining the analysis from Figure 7.5 and Figure 7.7, it implies that the changing asphalt binder of 50%RAP150 and 50%RAP200 affected the surface texture wearability (V_{mp} -the first tire/pavement contact area), but it does not impact the material properties of the core working region.

Figure 7.9 shows V_{vc} of the four test sections. Very similar characteristics of V_{mc}

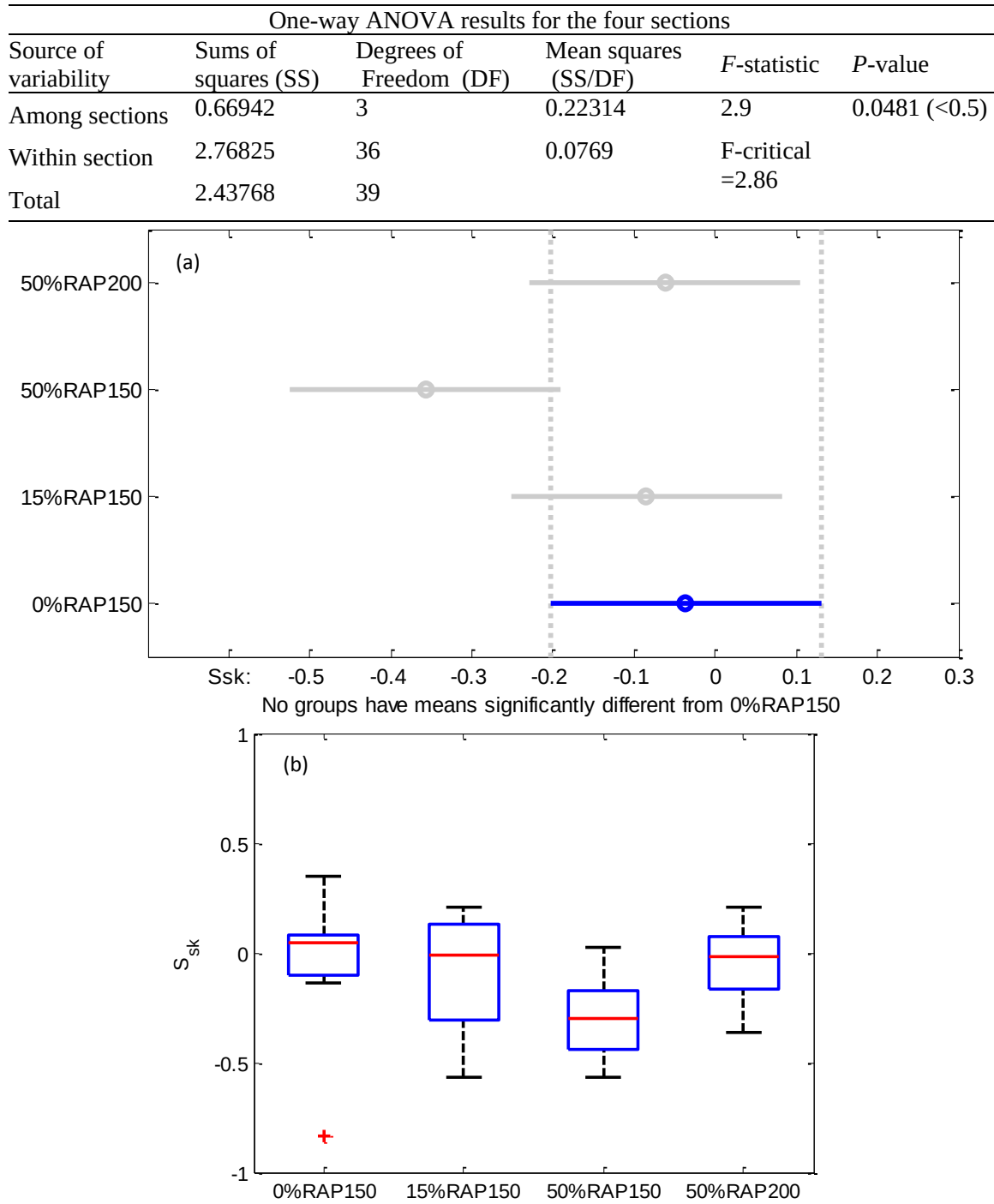


Figure 7.5: ANOVA of S_{sk} : (a) multiple comparison of means, confidence intervals and (b) boxplot of median, 25%/75% quantile.

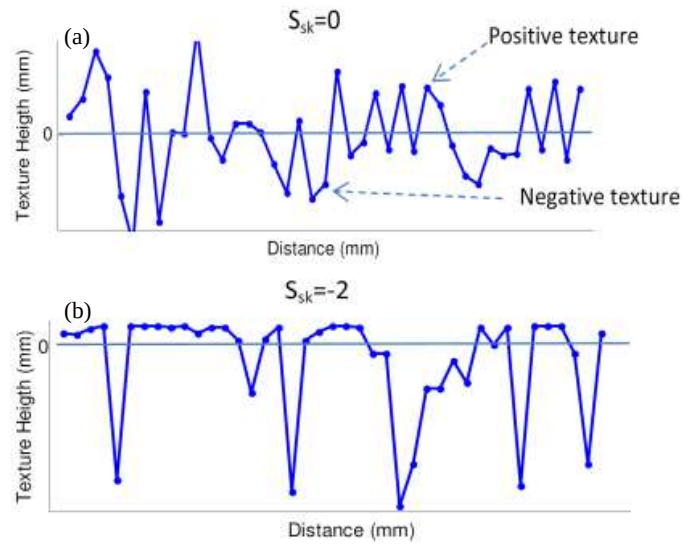


Figure 7.6: Texture profiles with zero mean and different skewness (a) Gaussian surface and (b) negatively skewed surface.

were found for V_{vc} as expected. As discussed in Figure 6.6 in section 6.3.1, the pavement friction is closely related to V_{vc} . This observation implies that the presence of RAP is helpful to pavement friction.

Figure 7.10 shows $NPSE$ of the four test sections. No significant difference was found for $NPSE$ among the four tested sections.

7.2.2 Summary of the Impacts of RAP on Pavement Texture

This study presented a side-by-side comparison of microtexture and macrotexture of asphalt pavement sections with various percentages of RAP content and two types of binders. It was found that, after five years of traffic and environmental loading, the presences of RAP resulted in higher macrotexture represented by simulated mean texture depth, root mean square roughness, volume material parameters. Or in other words, the presence of RAP has observed positive impacts on pavement friction or safety because the amplitude of macrotexture is positively related to pavement friction and safety. The change of binder

One-way ANOVA results for the four sections					
Source of variability	Sums of squares (SS)	Degrees of Freedom (DF)	Mean squares (SS/DF)	F-statistic	P-value
Among sections	58.645	3	19.5483	12.48	9.52424e-6
Within section	56.373	36	1.5659		
Total	115.018	39			

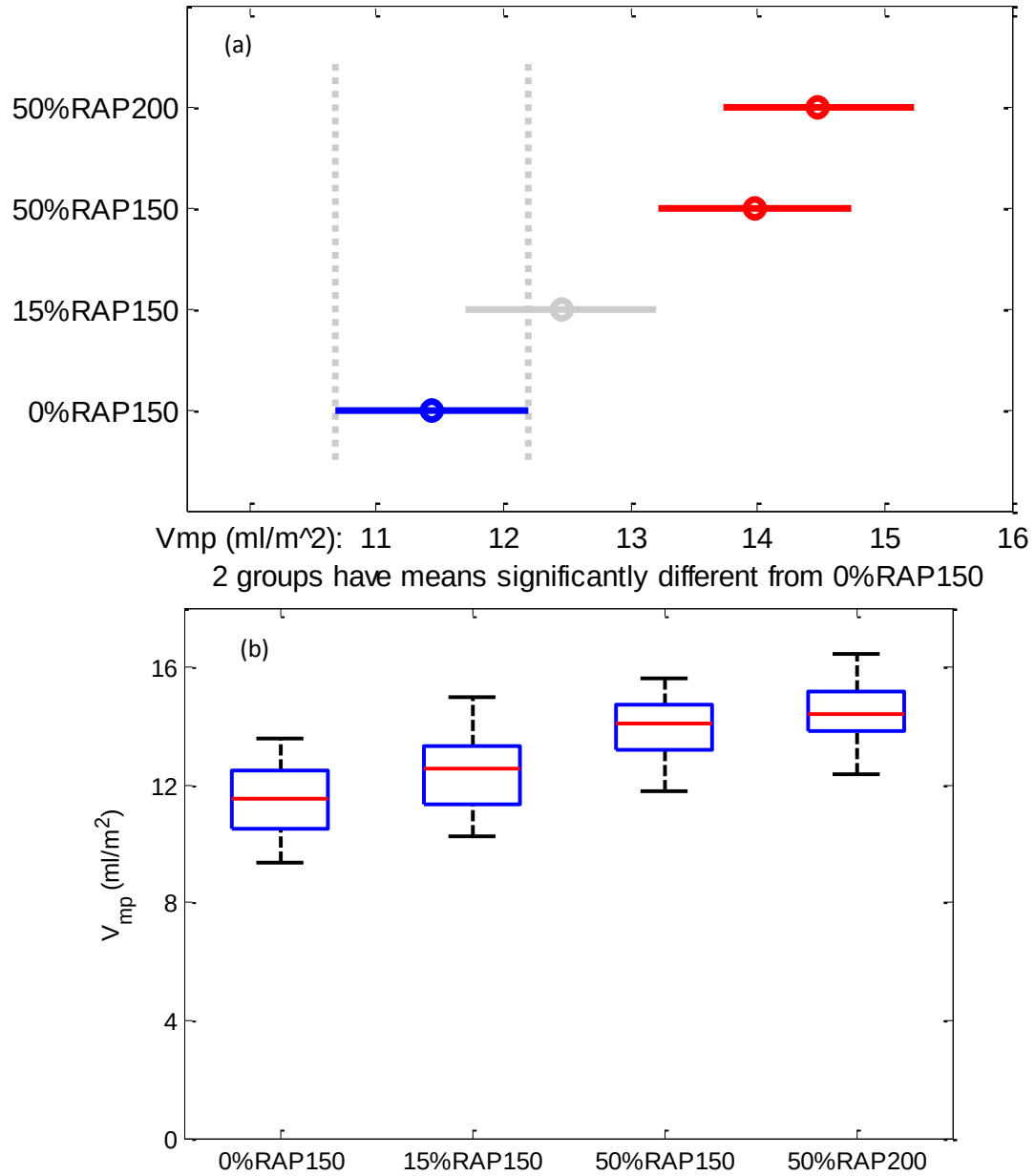


Figure 7.7: ANOVA of V_{mp} : (a) multiple comparison of means, confidence intervals and (b) boxplot of median, 25%/75% quantile.

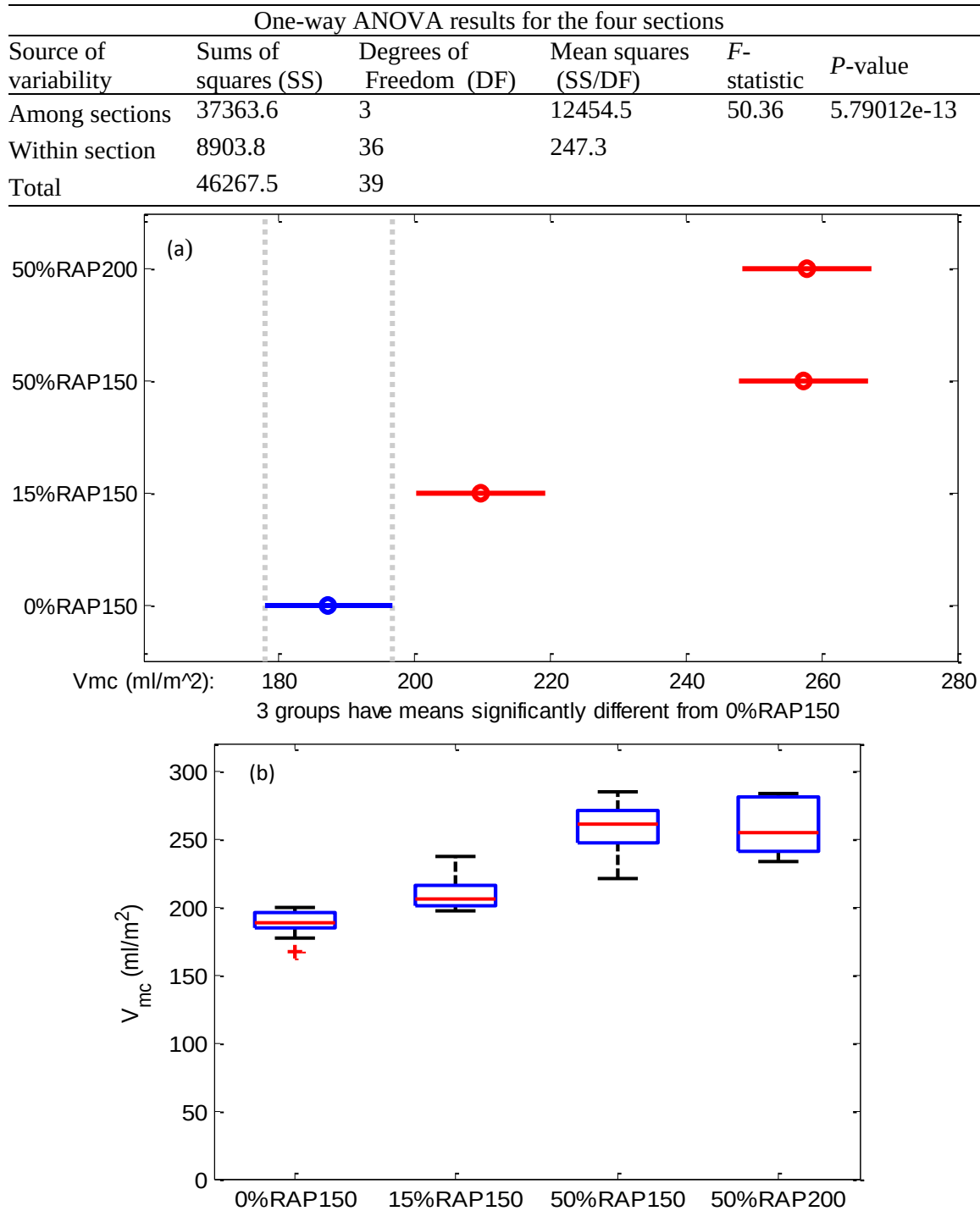


Figure 7.8: ANOVA of V_{mc} : (a) multiple comparison of means, confidence intervals and (b) boxplot of median, 25%/75% quantile.

One-way ANOVA results for the four sections					
Source of variability	Sums of squares (SS)	Degrees of Freedom (DF)	Mean squares (SS/DF)	<i>F</i> -statistic	<i>P</i> -value
Among sections	76186.9	3	25395.6	37.33	3.81232e-11
Within section	824490.2	36	680.3		
Total	100677.1	39			

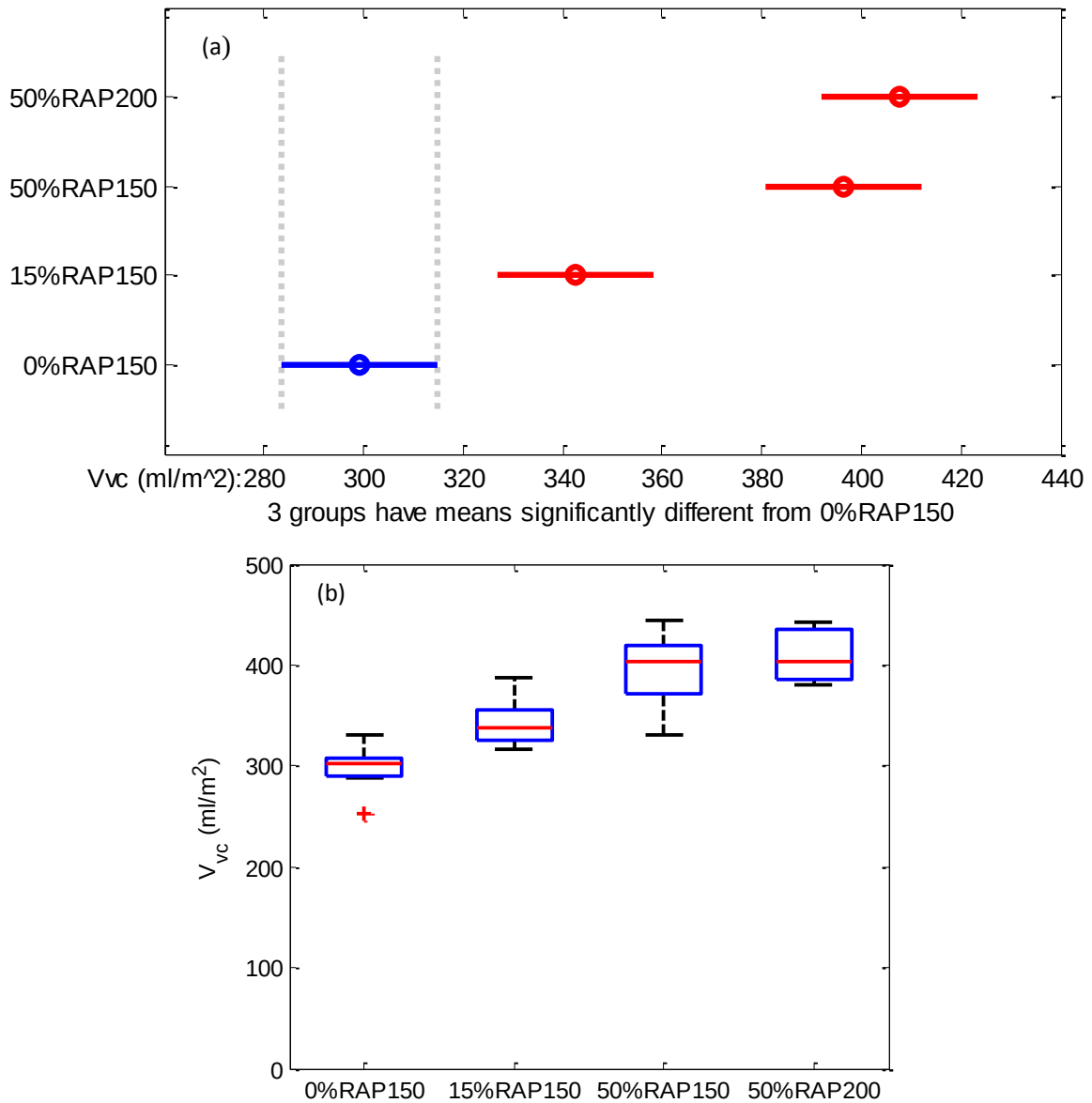


Figure 7.9: ANOVA of V_{vc} : (a) multiple comparison of means, confidence intervals and (b) boxplot of median, 25%/75% quantile.

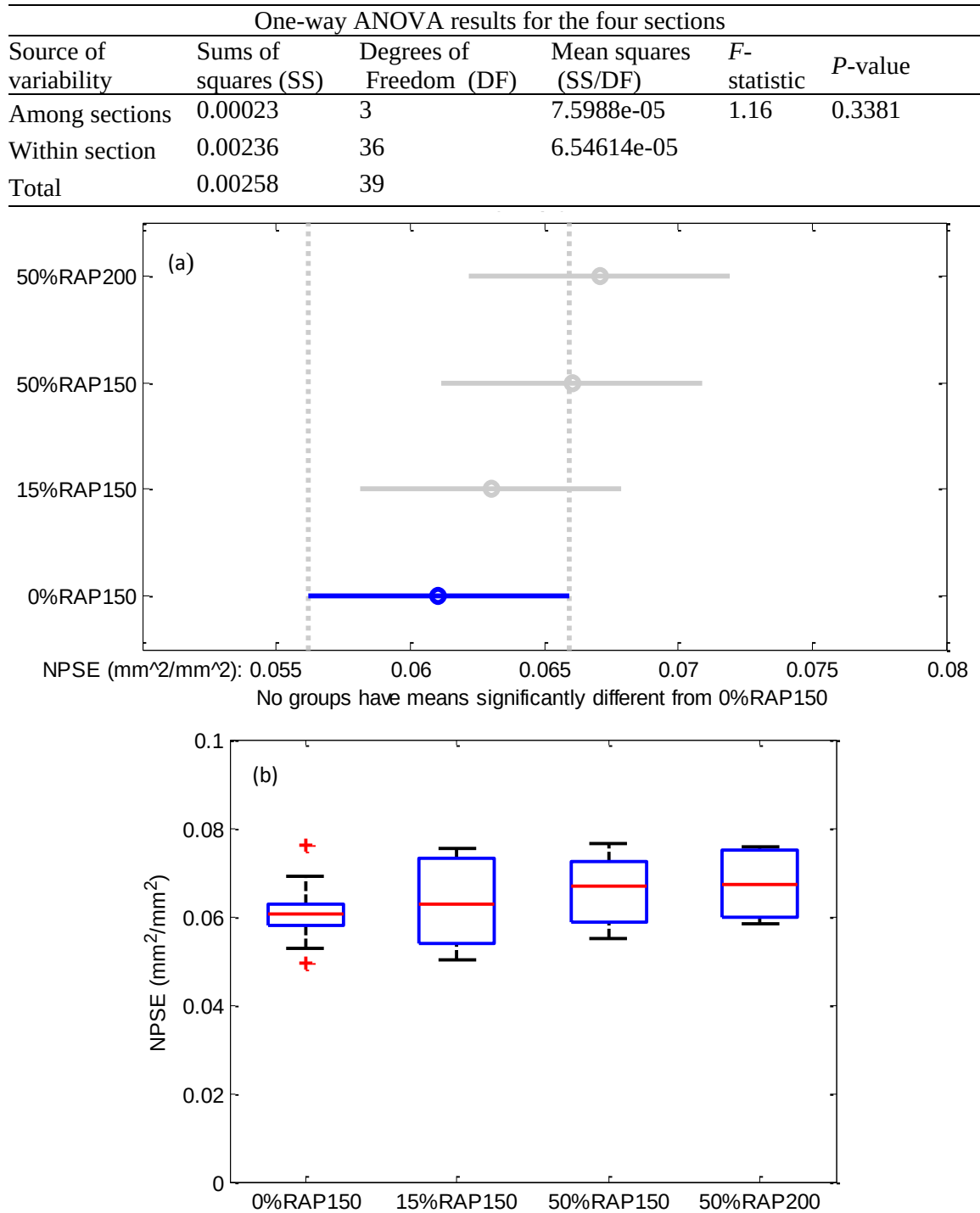


Figure 7.10: ANOVA of *NPSE* : (a) multiple comparison of means, confidence intervals and (b) boxplot of median, 25%/75% quantile.

from Pen 150-200 (PG 58-28) to Pen 200-300 (PG 52-34) does not have significant impact on the amplitude of macrotexture, but the changing of binders is helpful. The softer asphalt binder improved the surface texture wearability evidenced by more negative skewness and lower peak material volume of the section of 50%*RAP*150 with harder binder comparing to the section of 50%*RAP*200 which has softer asphalt binder. The presence of RAP does not show significant impact for pavement microtexture. The results of statistical analysis for pavement sections containing various percentage of RAP are summarized as shown in Table 7.5.

Table 7.5: Results of statistical analysis for pavements with various RAP.

Texture index (mean value)	Tested pavement sections (HMA with various RAP)				Statistical analysis at 95% confidence level	
	0% <i>RAP</i> 150 S1	15% <i>RAP</i> 150 S2	50% <i>RAP</i> 150 S3	50% <i>RAP</i> 200 S4	Pairwise comparison	P-value
SMTD (mm)	0.81	0.89	1.07	1.09	S1 ≠ [*] S3 S1 ≠ S4	1.26 ×10 ⁻⁰⁶
S _q (mm)	0.24	0.27	0.33	0.32	S1 ≠ S2 S1 ≠ S3 S1 ≠ S4 S2 ≠ S3 S2 ≠ S4	1.16 ×10 ⁻¹¹
S _{sk} (unitless)	-0.04	-0.08	-0.36	-0.06	none	0.0481
S _{ku} (unitless)	4.36	4.82	5.36	4.17	none	0.3884
V _{mp} (ml/m ²)	11.4	12.5	14.0	14.5	S1 ≠ S3 S1 ≠ S4	9.52 ×10 ⁻⁰⁶
V _{mc} (ml/m ²)	187.3	209.8	257.3	257.8	S1 ≠ S2 S1 ≠ S3 S1 ≠ S4	5.79 ×10 ⁻¹³
V _{vc} (ml/m ²)	299.1	342.4	396.4	407.7	S1 ≠ S2 S1 ≠ S3 S1 ≠ S4	3.81 ×10 ⁻¹¹
NPSE (mm ² /mm ²)	0.0611	0.0630	0.0660	0.0671	none	0.3381

*--Significantly different from

7.3 Assessing Surface Texture of Pavements with RAS

7.3.1 Test Site and Texture Measurement

Ryerson Avenue, a two lane residential roadway in Winnipeg, was selected for texture analysis to evaluate the impacts of RAS on surface texture. The pavement was overlaid in 2012 with 50 mm 3% RAS (its gradation is shown in Figure 7.11) HMA or 50mm Type-1A (standard) HMA overlays on concrete pavements. The RAS overlay was placed on the eastbound/northbound lane and the Type-1A (standard) overlay was placed on the westbound/southbound lane, over a distance of 0.7 kilometers, from Rice Road to Dalhousie Drive. The City of Winnipeg estimates the 2-way annual average daily traffic (AADT) on Ryerson Avenue at 333 vehicles per day. The pavement has been in service for two years and half at the time of testing. In addition to traffic loading, the tested pavement sections were exposed to extreme cold environmental conditions in Manitoba Canada.

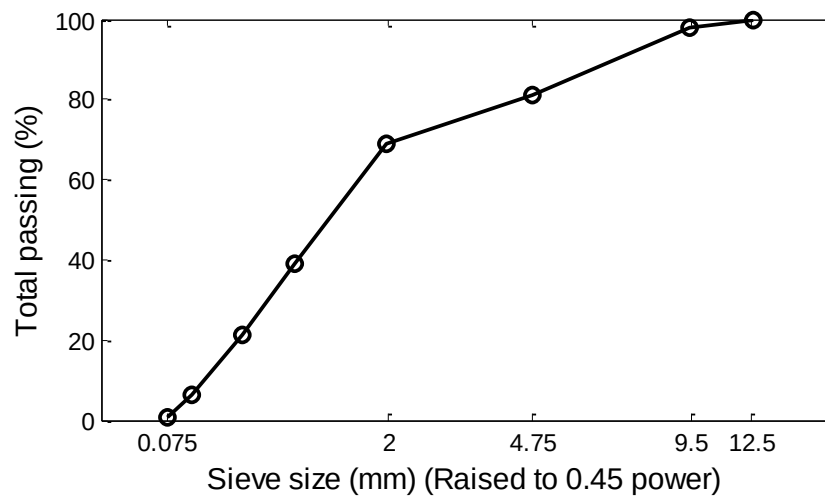


Figure 7.11: The gradation of RAS material.

Eleven replicate measurements, spaced 10 metres away from each other, were taken at four sets of locations, both inner wheel-path (close to the central line) and between

wheel-path for both control and RAS lanes. The pavement conditions and the locations of texture measurements were shown in Figure 7.12 and Figure 7.13.

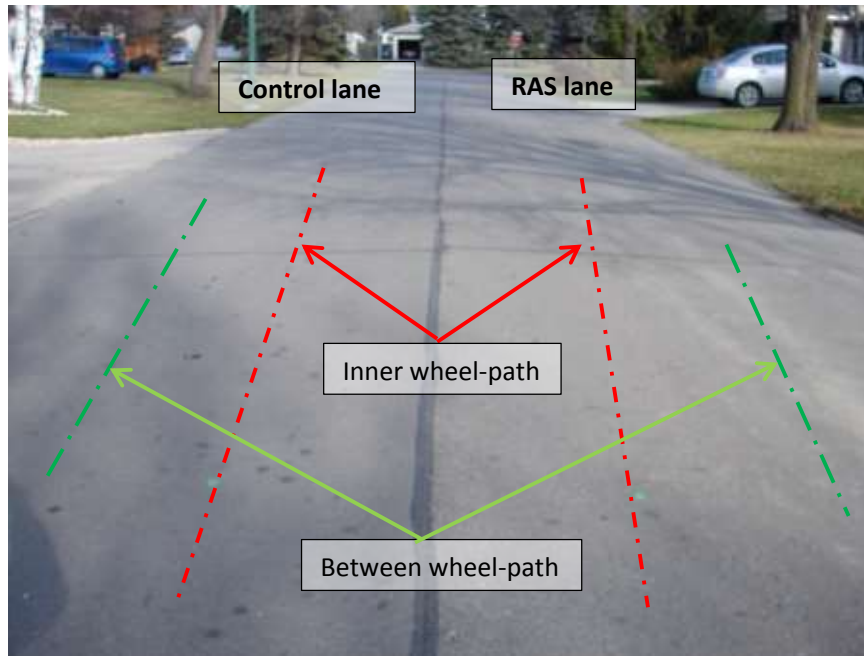


Figure 7.12: General view and measurement locations of the tested lanes.

The 3D texture parameter were shown in Table 7.6 and Table 7.7 for control lane and RAS lane, respectively. Similar to the investigation in section 7.2.1, ANOVA analysis was carried out to evaluate the impact of RAS on the calculated 3D texture parameters for the four sets of locations [Control lane between wheel-path (Control-Betw) , Control lane Inner wheel-path (Control-In), RAS lane between wheel-path (RAS-Betw), and RAS lane Inner wheel-path (RAS-In)], as shown in Figure 7.12].

7.3.2 Impact of RAS on Pavement Texture

Figure 7.14 shows the ANOVA results of SMTDs for the four sets of locations (Control-Betw, Control-In, RAS-Betw and RAS-In). The results of multiple comparison of the SMTDs were shown in Figure 7.14 (a), while the SMTDs were box-plotted as shown in

Table 7.6: Texture parameters of control lane.

Measure spot	SMTD	S_q	S_{sk}	S_{ku}	V_{mp}	V_{mc}	V_{vc}	V_{vv}	H_{10}	H_{80}	NPSE	
Between wheel path	1	0.62	0.17	-0.81	6.33	7.2	130.8	174.7	23.4	0.20	-0.12	0.0672
	2	0.58	0.16	-0.34	4.02	7.4	130.3	176.1	19.5	0.20	-0.12	0.0727
	3	0.52	0.19	-1.11	6.77	6.3	149.9	190.9	27.8	0.22	-0.13	0.0683
	4	0.39	0.14	-0.54	3.82	5.1	118.4	150.2	17.8	0.17	-0.11	0.0672
	5	0.42	0.13	-0.68	4.32	4.9	108.4	136.9	18.2	0.15	-0.10	0.0808
	6	0.44	0.14	-0.88	5.04	4.4	116.4	141.4	19.8	0.16	-0.10	0.0890
	7	0.63	0.19	-0.81	5.45	7.5	149.9	190.7	25.2	0.22	-0.13	0.0918
	8	0.59	0.16	-0.86	5.79	7.1	126.8	159.3	23.9	0.18	-0.11	0.0926
	9	1.26	0.26	-2.5	23.5	10.8	181.7	242.5	33.4	0.28	-0.16	0.0842
	10	0.56	0.15	-1.23	8.68	5.7	115.6	146.9	21.5	0.17	-0.10	0.0919
	11	0.46	0.15	-1.14	7.24	5.6	118.1	150.5	21.4	0.17	-0.10	0.0876
	Ave	0.59	0.17	-0.99	7.36	6.5	131.5	169.1	22.9	0.19	-0.12	0.0812
Std	0.24	0.04	0.56	5.54	1.8	21.4	30.8	4.6	0.03	0.02	0.0105	
Inner wheel path	1	0.43	0.12	-0.78	4.44	4.2	101.5	123.6	17.6	0.14	-0.09	0.0834
	2	0.35	0.12	-0.78	4.90	4.2	102.7	130.0	17.1	0.15	-0.09	0.0772
	3	0.31	0.13	-1.15	6.04	3.8	103.9	125.1	19.5	0.14	-0.09	0.0710
	4	0.42	0.13	-0.51	3.82	5.1	111.4	141.8	16.5	0.16	-0.10	0.0691
	5	0.38	0.13	-0.90	4.93	4.4	103.4	125.1	19.2	0.15	-0.09	0.0756
	6	0.37	0.13	-1.02	5.76	4.4	107.7	129.3	19.1	0.15	-0.10	0.0893
	7	0.46	0.15	-0.73	4.94	5.5	121.3	157.1	19.7	0.18	-0.11	0.0906
	8	0.36	0.15	-1.50	8.38	4.4	114.7	135.5	24.0	0.16	-0.10	0.0917
	9	0.82	0.18	-1.38	9.44	6.7	136.3	173.5	26.5	0.20	-0.12	0.0939
	10	0.47	0.13	-0.74	5.19	4.9	103.9	131.5	18.1	0.15	-0.09	0.0915
	11	0.56	0.16	-0.79	5.13	5.9	124.0	161.0	21.5	0.18	-0.11	0.0896
	Ave	0.45	0.14	-0.93	5.73	4.9	111.9	139.4	19.9	0.16	-0.10	0.0839
Std	0.14	0.02	0.30	1.70	0.9	11.2	17.0	3.0	0.02	0.01	0.0091	

Where

Ave = Averaged value of the 10 replicate measurements

Std = Standard deviation

SMTD = simulated mean texture depth (mm)

S_q = Root mean square deviation (mm)

S_{sk} = Skewness of texture height map

S_{ku} = Kurtosis of texture height map

V_{mp} = Peak material volume (ml/m²)

V_{mc} = Core material volume (ml/m²)

V_{vc} = Core void volume (ml/m²)

V_{vv} = Valley material volume (ml/m²)

H_{10} (H_{80}) = Texture height corresponding to 10% (80%) material ratio of the bearing area curve (mm)

NPSE = Normalized power spectral energy (mm²/mm²)

Table 7.7: Texture parameters of RAS lane.

Measure spot	SMTD	S_q	S_{sk}	S_{ku}	V_{mp}	V_{mc}	V_{vc}	V_{vv}	H_{10}	H_{80}	NPSE	
Between wheel path	1	0.47	0.19	-0.9	4.8	4.9	160.1	193.2	27.8	0.22	-0.14	0.0741
	2	0.50	0.15	-0.7	4.2	5.3	125.6	158.6	20.9	0.18	-0.11	0.0687
	3	0.61	0.16	-1.1	6.3	5.4	128.6	150.7	23.3	0.18	-0.11	0.0762
	4	0.41	0.15	-1.0	5.4	4.2	123.0	148.4	21.1	0.17	-0.11	0.0687
	5	0.31	0.09	-1.0	6.0	3.2	76.4	92.5	13.6	0.11	-0.07	0.0690
	6	0.39	0.15	-1.4	7.9	4.0	114.1	138.5	22.5	0.16	-0.10	0.0895
	7	0.83	0.13	-0.8	4.6	4.6	107.9	133.2	18.8	0.15	-0.10	0.0928
	8	0.42	0.17	-1.6	8.9	4.3	127.6	144.2	26.0	0.18	-0.11	0.0901
	9	0.62	0.18	-1.7	24.1	5.7	138.5	173.5	28.0	0.20	-0.12	0.0984
	10	0.46	0.16	-1.8	10.6	4.4	124.6	145.7	26.4	0.17	-0.11	0.0931
	11	0.49	0.13	-1.0	5.2	3.9	104.3	120.9	18.7	0.14	-0.09	0.0918
	Ave	0.50	0.15	-1.17	8.0	4.5	121.0	145.4	22.5	0.17	-0.11	0.0830
Std	0.14	0.03	0.38	5.68	0.7	21.1	26.2	4.5	0.03	0.02	0.0116	
Inner wheel path	1	0.74	0.26	-0.8	4.8	8.9	214.6	271.2	33.5	0.31	-0.19	0.0802
	2	0.84	0.26	-1.2	7.1	8.2	199.1	248.9	38.1	0.29	-0.18	0.0741
	3	0.59	0.20	-0.9	4.9	6.3	159.7	193.7	28.9	0.22	-0.14	0.0725
	4	0.54	0.19	-1.5	9.8	6.1	140.0	178.9	28.1	0.21	-0.12	0.0676
	5	0.38	0.14	-1.6	8.9	3.7	103.0	119.9	22.1	0.14	-0.09	0.0671
	6	0.40	0.13	-0.9	6.4	5.2	101.7	129.0	17.1	0.15	-0.09	0.0966
	7	0.67	0.21	-1.4	8.7	7.9	156.8	193.8	31.2	0.23	-0.14	0.0932
	8	0.61	0.17	-0.9	5.2	6.0	134.2	158.4	24.1	0.18	-0.12	0.0943
	9	1.05	0.25	-1.0	5.8	9.1	197.8	242.2	39.2	0.29	-0.17	0.0928
	10	0.86	0.20	-1.9	14.3	7.0	145.5	174.7	29.4	0.21	-0.12	0.0958
	11	0.76	0.28	-1.4	7.4	9.4	203.2	244.7	46.3	0.29	-0.17	0.0877
	Ave	0.68	0.21	-1.2	7.6	7.1	159.6	195.9	30.7	0.23	-0.14	0.0838
Std	0.20	0.05	0.37	2.80	1.8	39.7	50.4	8.3	0.06	0.03	0.0118	

Where

Ave = Averaged value of the 10 replicate measurements

Std = Standard deviation

SMTD = simulated mean texture depth (mm)

 S_q = Root mean square deviation (mm) S_{sk} = Skewness of texture height map S_{ku} = Kurtosis of texture height map V_{mp} = Peak material volume (ml/m^2) V_{mc} = Core material volume (ml/m^2) V_{vc} = Core void volume (ml/m^2) V_{vv} = Valley material volume (ml/m^2) H_{10} (H_{80}) = Texture height corresponding to 10% (80%) material ratio of the bearing area curve (mm)NPSE = Normalized power spectral energy (mm^2/mm^2)

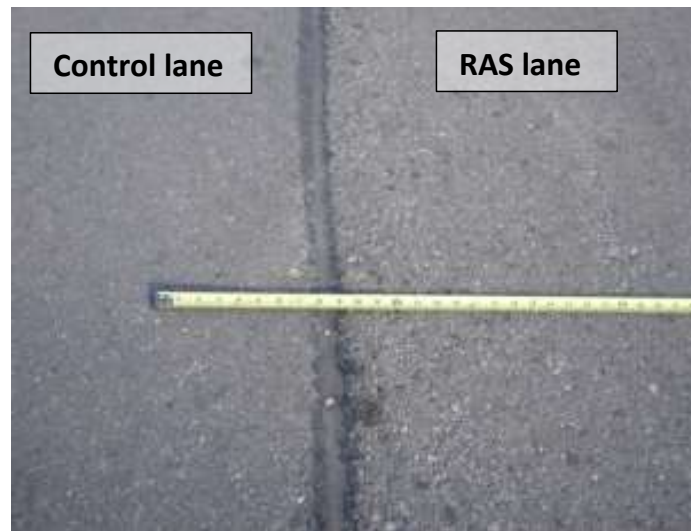


Figure 7.13: A close look at the tested lanes.

Figure 7.14 (b). The central mark is the median, the edges of the box are 25th and 75th percentiles. The outliers were plotted individually.

From Figure 7.14 (a), it was observed, at confidence level of 95%, that:

1. the SMTDs of two inner wheel-paths (Control-In, RAS-In) are significantly different.
2. the SMTDs of Control-Betw and RAS-Betw are not significantly different.
3. the SMTDs of Control-Betw and Control-In are not significantly different.
4. the SMTDs of RAS-Betw and RAS-In at the RAS lane are not significantly different.

It is understandable that traffic volume/pattern is different between inner wheel-path and between wheel-path for either control lane or RAS lane. It can be concluded that traffic loading in this study is not a significant factor for surface texture indices based on observations of 3 and 4 above. For example, SMTDs for Control-Betw and Control-in are not significantly different although traffic volume/pattern might be different for Control-Betw and Control-in (pavement mixes (material) are the same for these two locations), which indi-

cates that traffic loading in this study is not a significant factor for surface texture indices. Possible reason is that the AADT is only 333 vehicles per day for two-way traffic.

It was assumed that the traffic loading of the two inner wheel-paths (Control-In, RAS-In) are similar based on the following reasons:

- The Ryerson Avenue is a local street in Fort Richmond, Winnipeg with 333 vehicles per day. The RAS lane serves also as parking lane, the traffic volume and patterns of the RAS and control lanes are different.
- The inner wheel-paths of both control lane and RAS lane are very close to each other ($\leq 80cm$), as can be seen from Figure 7.12. It was observed that most vehicles were driving in the middle of the road.

It is reasonable to conclude that it is the presence of RAS that made the SMTDs of two inner wheel-paths (Control-In, RAS-In) significantly different. RAS in this research improved the surface texture at the time of this evaluation.

The ANOVA for S_q was plotted as shown in Figure 7.15. As can be seen from Figure 7.14 and Figure 7.15, it can be concluded that the presence of 3% of RAS significantly affected the texture amplitude ($SMTD$) and its variation (S_q) of the pavement surface. There is no significant difference of the texture S_{sk} as can be seen from Figure 7.16. As shown in Figure 7.17 and Figure 7.18, the V_{mc} and V_{vc} are significantly different between the inner wheel-path of control lane and RAS lane. As discussed in section 6.3.1, the V_{mc} or V_{vc} is positively related to pavement friction. As shown in Figure 7.18, There is no significant difference of the microtexture index, $NPSE$ of all the four tested wheel-paths.

In summary, the presence of 3% of RAS made the macrotexture parameters ($SMTD$, S_q , V_{mc} , and V_{vc}) significantly higher than those of control lane. However the distribution of the macrotexture represented by S_{sk} or S_{ku} did not show any significant difference. The presence of RAS did not have significant impact on the microtexture index, $NPSE$.

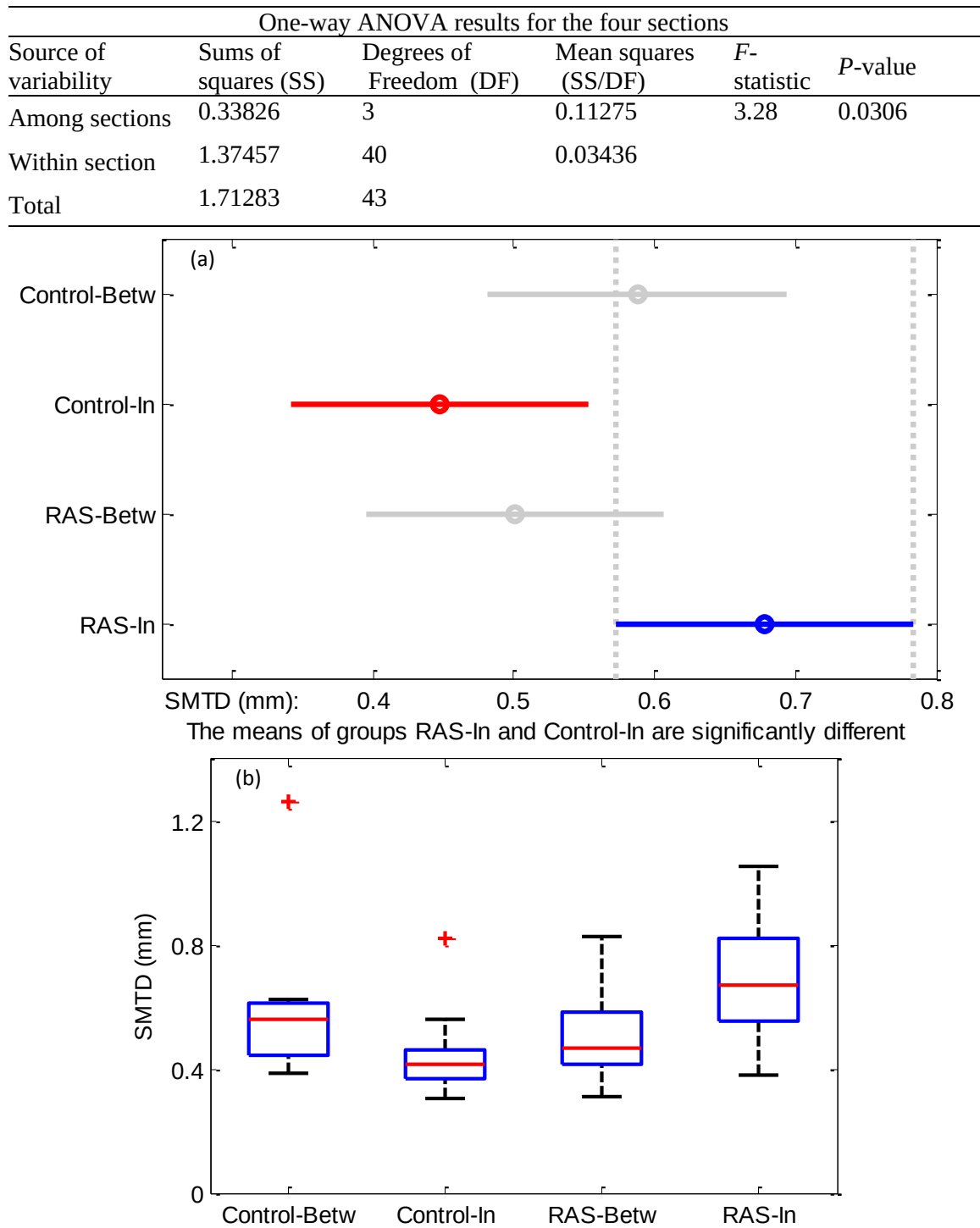


Figure 7.14: ANOVA of *SMTD* with RAS : (a) multiple comparison of means, confidence intervals and (b) boxplot of median, 25%/75% quantile.

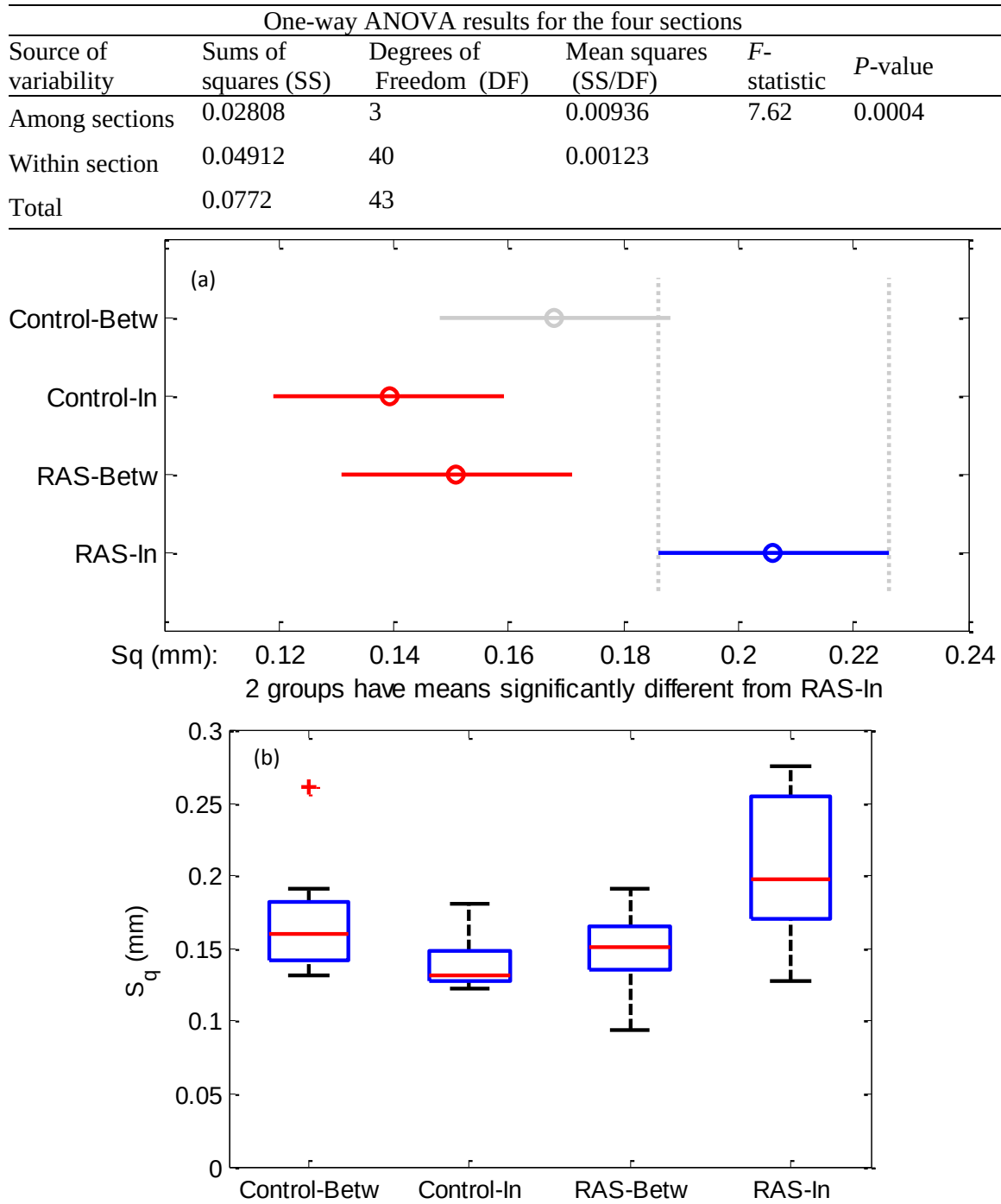


Figure 7.15: ANOVA of S_q with RAS : (a) multiple comparison of means, confidence intervals and (b) boxplot of median, 25%/75% quantile.

One-way ANOVA results for the four sections					
Source of variability	Sums of squares (SS)	Degrees of Freedom (DF)	Mean squares (SS/DF)	F-statistic	P-value
Among sections	0.64976	3	0.21659	1.26	0.3016
Within section	6.88486	40	0.17212		
Total	7.53462	43			

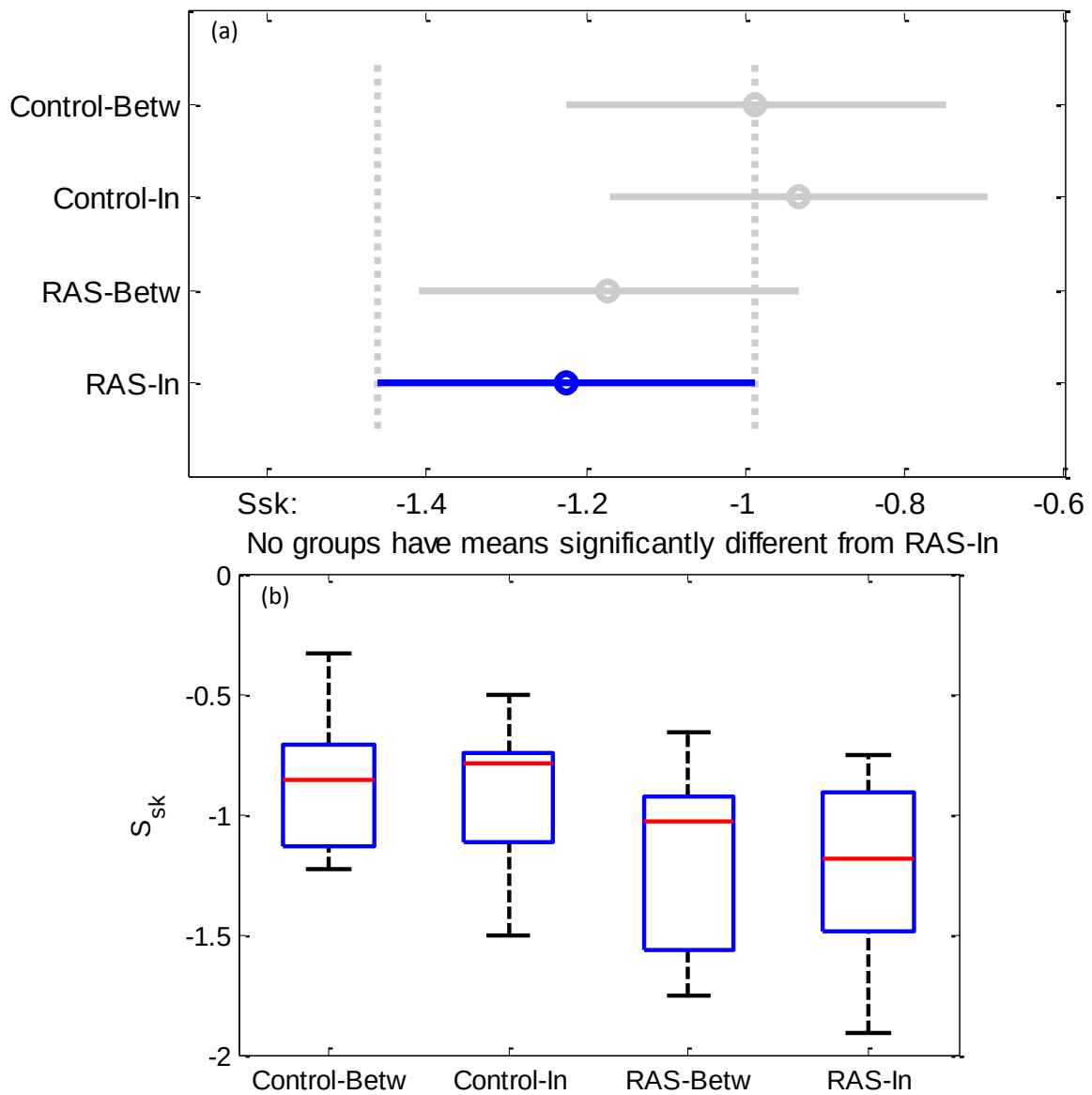


Figure 7.16: ANOVA of S_{sk} with RAS : (a) multiple comparison of means, confidence intervals and (b) boxplot of median, 25%/75% quantile.

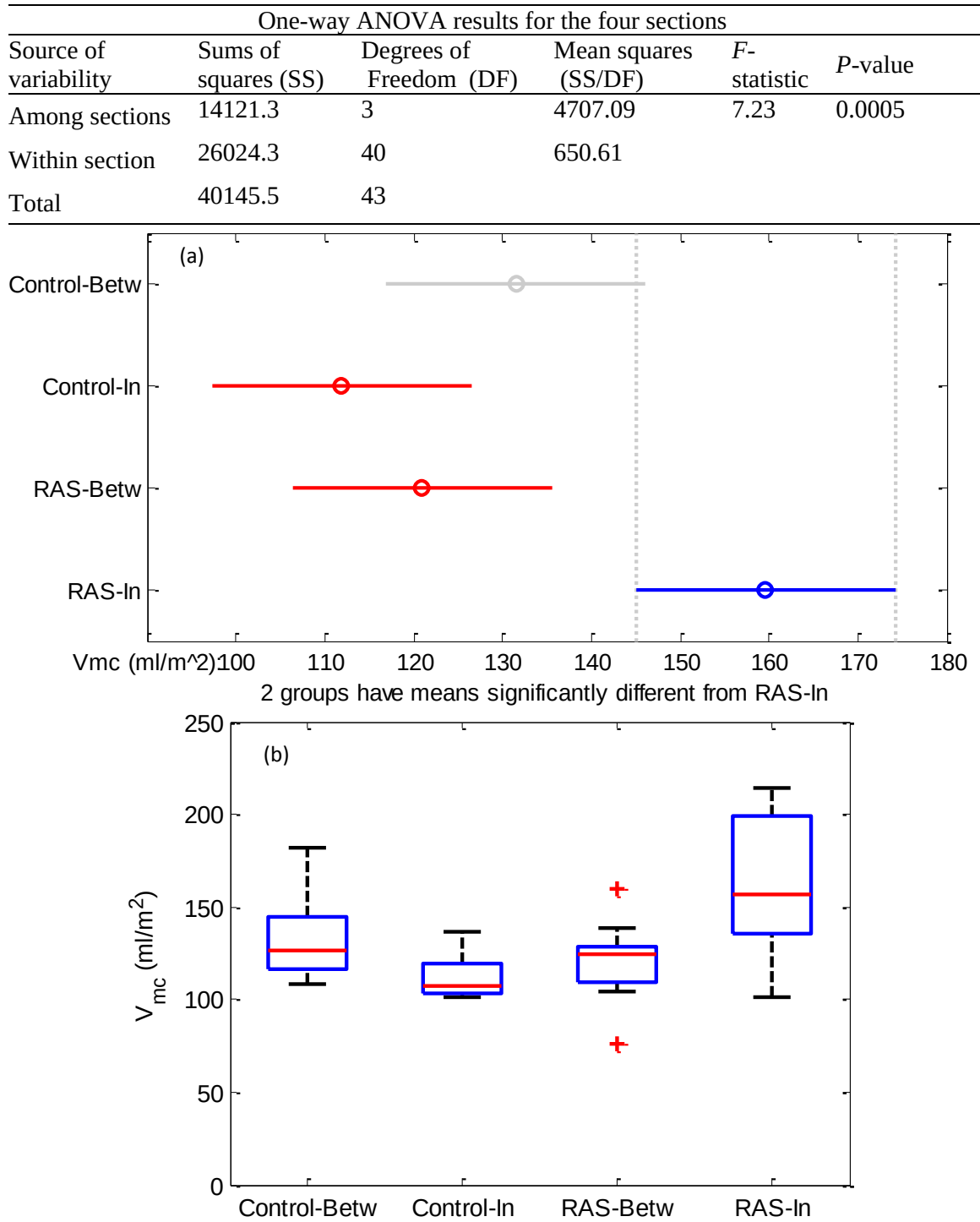


Figure 7.17: ANOVA of V_{mc} with RAS : (a) multiple comparison of means, confidence intervals and (b) boxplot of median, 25%/75% quantile.

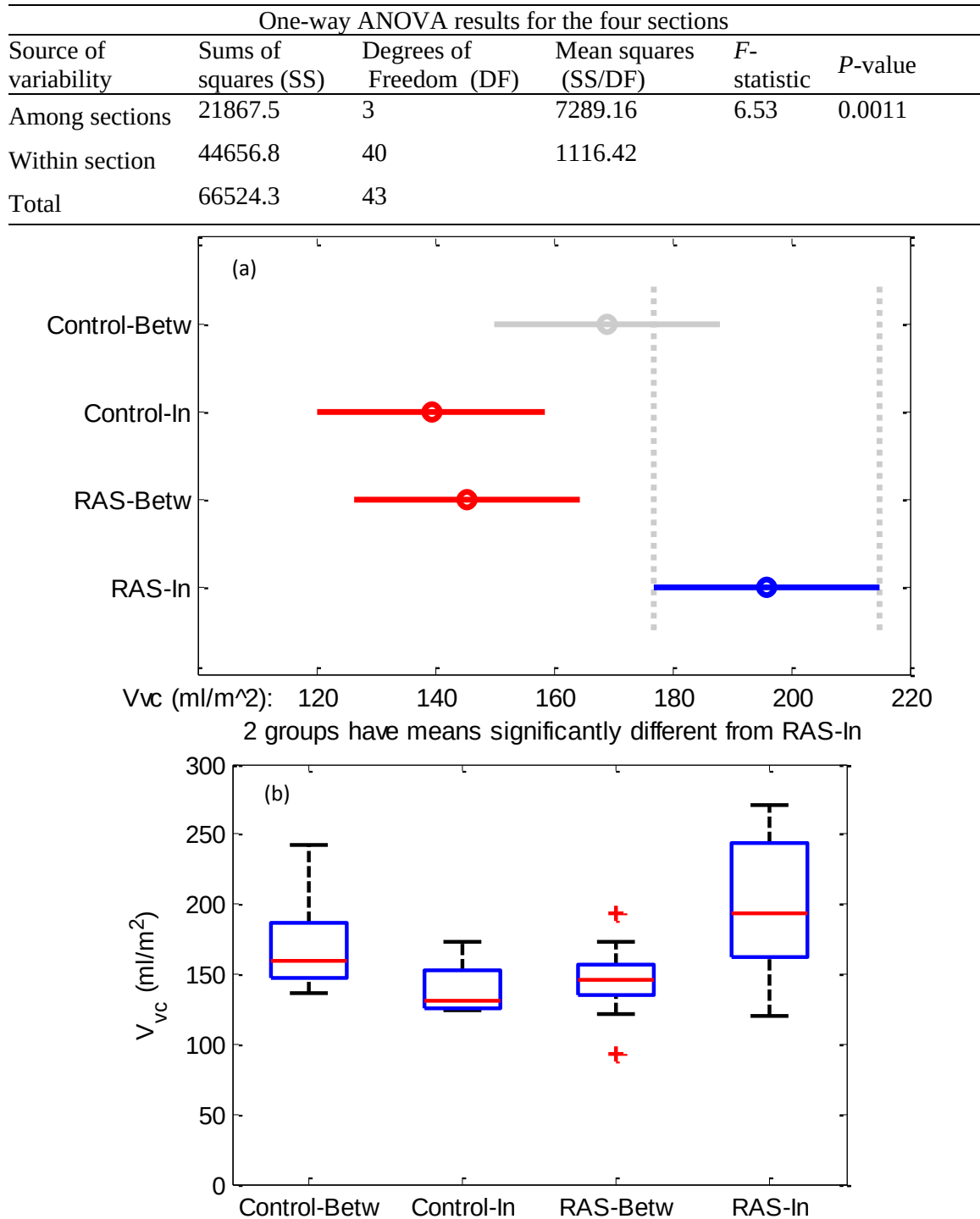


Figure 7.18: ANOVA of V_{vc} with RAS : (a) multiple comparison of means, confidence intervals and (b) boxplot of median, 25%/75% quantile.

One-way ANOVA results for the four sections					
Source of variability	Sums of squares (SS)	Degrees of Freedom (DF)	Mean squares (SS/DF)	F-statistic	P-value
Among sections	0.00005	3	0.00002	0.15	0.9306
Within section	0.00464	40	0.00012		
Total	0.00469	43			

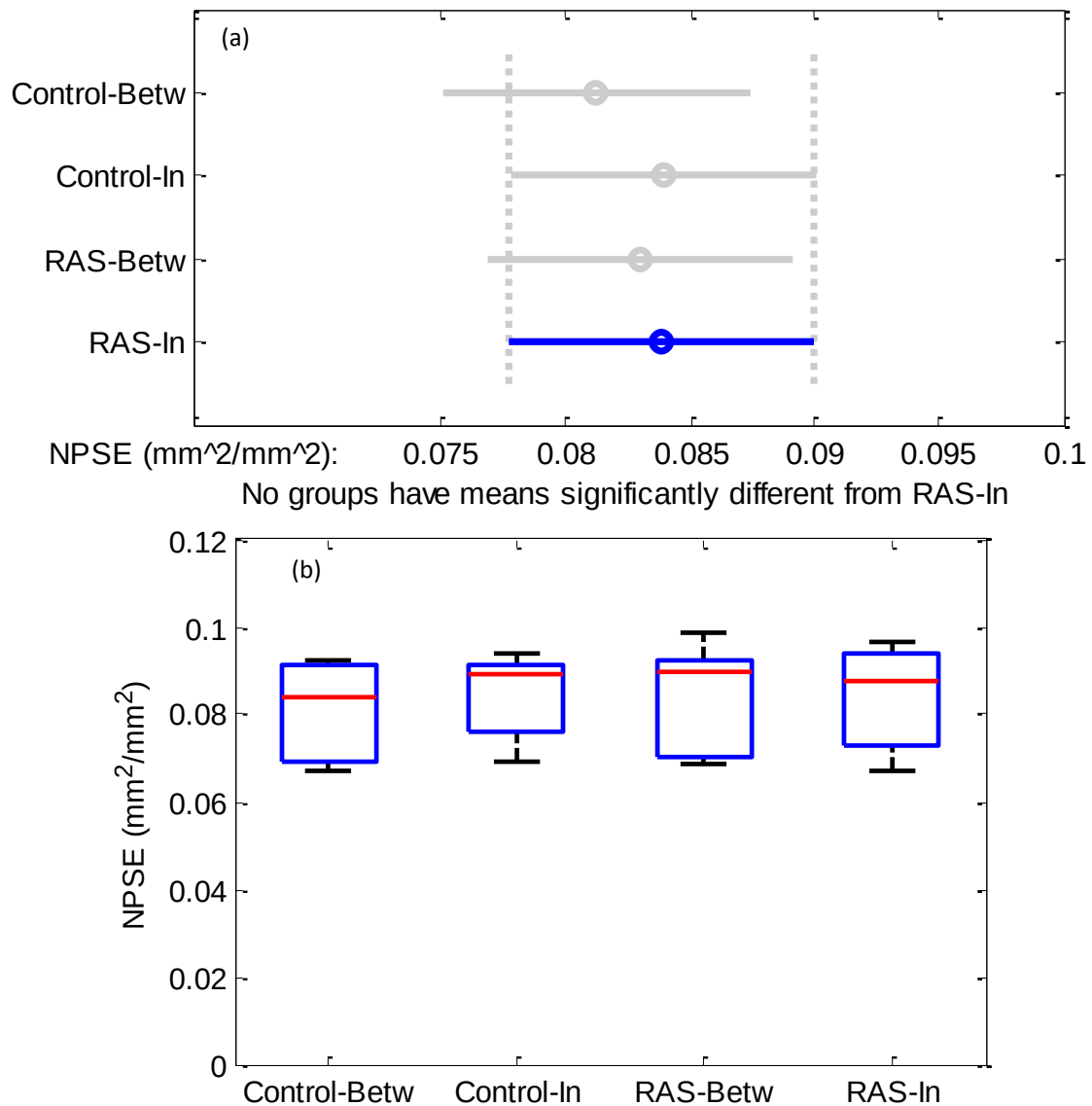


Figure 7.19: ANOVA of $NPSE$ with RAS : (a) multiple comparison of means, confidence intervals and (b) boxplot of median, 25%/75% quantile.

Chapter 8

CONCLUSIONS

8.1 Summary and Contributions

The measurement of surface texture has been of primary importance of pavement professionals for decades. However the pavement texture was still measured dominantly by either contact methods or 2D profile based non-contact methods in the transportation industry – although researchers have discussed the limitations of 2D profile methods especially when pavement friction and noise being involved. In the transportation industry, 3D pavement surface texture measurement has not been well established. The available 3D pavement texture methods measure macrotexture with applications focused on PCC pavement joint faulting measurement (Wang and Li, 2014), pavement cracking measurement (Ouyang and Xu, 2013), and rutting measurement (Austroad, 2009, Tsai et al., 2013). There is no established 3D texture parameters are available to characterize pavement surface texture. To the author’s knowledge, there no documents available to explore relationship between 3D texture parameters and the 2D profile based parameters for the purposes of data comparison or quality assurance when equipment is of different dimensions. There are no documents available to explore appropriately relationship between 3D texture parameters and pavement friction or noise.

Recover Pavement Surface into 3D Texture Height Map

Various types of pavement surface texture were measured in this thesis by using either photometric stereo method or line-laser scanner. With a horizontal resolution better than 0.05 mm, it was able to measure both microtexture ($\leq 0.5mm$) and macrotexture ($0.5mm - 50mm$) by using the line-laser scanner. The measured pavement surface areal

topography was recovered into 3D texture height map after being detrended to remove the average elevation and slope for the purpose of normalization.

Discrete Wavelet Transform to Analyze 3D Texture Height Map

The 3D texture height map was analyzed by using discrete wavelet transform to decompose the 3D texture height map into approximate component to represent the macrotexture and four levels of detailed components to represent microtexture at various wavelength bands. Texture parameters were calculated independently for microtexture and macrotexture.

Proposed 3D Texture Parameters

Based on the 3D parameters and texture measurement practices from transportation engineering and manufactured industry, this thesis proposed two sets of 3D parameters to characterize pavement macrotexture:

- Texture amplitude related 3D parameters including $SMTD$, S_q , S_{sk} , and S_{ku} .
- Material volume of the recovered 3D texture height map related parameters including V_{mp} , V_{mc} , V_{vc} , and V_{vv} . These parameters represent surface function as peak (first contact) region (V_{mp}), core region (V_{mc} and V_{vc}), and valley region (V_{vv}).

One 3D index was defined to characterize pavement microtexture:

- Normalized power spectra energy ($NPSE$). NPSE is based on the power spectrum of the various decomposition levels of the discrete wavelet transform of the measured 3D texture height map.

Field Tests

The proposed 3D texture parameters and the research methodology were applied and tested in various pavements with numerous types of textures and materials:

- Texture test at interstate highway. The South Extension of the I-355 North-South Tollway between I-55 and I-80 near Joliet, Illinois. Thirteen types of PCC surface texture were measured by using photometric stereo device. Three-dimensional text parameters were verified by 2D MPD from established CTM method.
- Texture test at MnROAD test facilities. Simultaneous line-laser scanner and CTM testing were conducted on six pavement cells at the MnROAD test facilities to compare 3D and 2D texture measurements.
- Texture test at airport runway. Texture was measured at runway 13-31 of James Armstrong Richardson International Airport (Winnipeg) by using line-laser scanner for AC pavement and PCC pavement with various texture types. The relationship between pavement surface texture and pavement friction was explored.
- Texture test at sections of Manitoba provincial trunk highway 8. The Manitoba Infrastructure and Transportation in collaboration with the Asphalt Research Consortium built, in 2009, these pavement sections with high RAP contents (15% and 50%) to provide necessary information for assessing the impact of high RAP content in surface layers in cold weather regions. The texture test at these sections was to evaluate the impact of high RAP contents on pavement surface texture.
- Texture test at local street. Texture was measured at Ryerson Avenue Winnipeg. Pavement sections with RAP content of 10% and recycled asphalt shingles (RAS) of 0% or 3%. These pavement sections have been in service for two years. The objective of this test is to evaluate the impacts of RAS on pavement surface texture.

Verification and Statistical Analysis of the 3D Texture Indices

The proposed 3D parameters for macrotexture were verified by established 2D texture measurement (e.g. CTM) method. An excellent relationship with R^2 value of 0.83 was found between MPD (2D) and SMTD (3D), while the R^2 value of 0.98 was found between $RMSR$ (2D) and S_q (3D).

This thesis has also explored the relationship between the 3D texture parameters and pavement friction and noise. In addition to the significant relationship between texture amplitude (SMTD) and friction/noise, the contribution of texture distribution and shape represented by S_{sk} or S_{ku} to pavement friction was also qualitatively evaluated which were not achievable for other studies.

The impacts of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) on pavement surface texture were also assessed in this thesis, which was not executed in other studies.

Contributions

The contributions of the thesis are summarized as follows:

- A methodology with discrete wavelet transform (DWT) was proposed to decompose the 3D pavement height maps to separate macrotexture from microtexture and calculate the texture parameters independently.
- Two sets of 3D parameters were defined to characterize pavement macrotextures: the texture amplitude related set ($SMTD$, S_q , S_{sk} , and S_{ku}) and the material volume related set (V_{mp} , V_{mc} , V_{vc} , and V_{vv})
- Normalized power spectra energy ($NPSE$) was defined as an index to represent pavement microtexture.
- The proposed 3D texture parameters were verified by established 2D methods and parameters in various types of pavement.

- The relationship between 3D macrotexture parameters and pavement friction and noise were established.
- The contribution of skewness and kurtosis (S_{sk} and S_{ku}) of surface texture to pavement friction and noise was quantitatively investigated.
- The relationship between volumetric parameter, V_{vc} , for instance, and pavement friction was also quantitatively investigated.
- The impacts of various percentage of RAP/RAS content on conventional hot mix asphalt pavement surface texture were evaluated for green pavement solution.

8.2 Limitations and Recommended Future Work

Researchers (Henry, 2000, Sandburg and Ejsmont, 2002b) have found that microtexture is important to pavement friction although no quantitative relationship was documented between microtexture and pavement friction. The microtexture index, NPSE, defined in this thesis was not found a significant contributor to pavement friction. A possible reason is that pavement friction was measured at 60km/h with water being dispensed onto the pavement immediately ahead of the test tire, while pavement texture was recovered in stationary manner with dry pavement condition in this thesis. Studies have found that microtexture is mainly responsible for pavement friction at low speeds and dry pavement condition (Bitelli et al., 2012). It is suggested to investigate pavement friction in stationary manner on dry pavement surface in order to explore the relationship between pavement friction and NPSE.

The recovered 3D texture height map was decomposed into four detailed levels to characterize the features of microtexture. The wavelength band of the four levels are: 0.06 mm and lower, 0.06-0.12 mm, 0.12-0.24 mm, and 0.24-0.49 mm. The NPSE is defined as the summation of the square of microtexture heights for all the four levels as shown in

Equation (3.13). It is suggested to investigate the characteristics of microtexture and its contribution to pavement friction and noise in each wavelength band.

The dimension of 3D texture height map in this thesis is 100×100 mm. The line-laser scanner is able to measure pavement surface texture up to 100×254 mm at a single set up. It is suggested to investigate a larger area in order to explore texture characteristic in the larger wavelength band.

The research methodology in this thesis can be employed to explore texture characteristics of construction materials of pavement mixture, e.g. the texture features of aggregate, aggregate size and distribution. It is possible to investigate the relationship between the texture characteristics of aggregate and the texture feature of designed/finished pavement surface. Eventually the texture characteristics of aggregate can be incorporated into design specifications for high friction pavement.

The method developed in this thesis can be used to track surface wear of roadways to evaluate the polishing effect of traffic on pavement texture.

The research methodology has been adopted to investigate pavement texture of interstate highway, research facilities at MnROAD, runways of airport, Manitoba truck highway, and municipal street in Winnipeg. Another important scenario is the intersection of busy streets where frequent stops or accelerations occur. Pavement distress and texture features at intersections are very different from other area. Adequate pavement friction at any intersection is important to the safety of pedestrians. It will be useful to investigate the texture features and to explore the relationship between texture and friction of intersection pavement.

For network level pavement surface texture evaluation, the line-laser scanner could be mounted further to increase the productivity of data collection and texture assessment.

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Appendix

Appendix A

CALIBRATION OF LINE-LASER SCANNER

This appendix outlines the procedures to calibrate the line-laser scanner (LS-40 Scanner) at the Transportation Research Group Laboratory. Since the scanner has the ability to recover 3D texture height map, the calibration was conducted longitudinally, transversely, and vertically.

A.1 Horizontal Error Distribution and Its Calibration

A.1.1 Calibration Tools

The devices and tools used in this calibration are: a line-laser scanner or LS-40 scanner and a piece of smooth surface. The LS-40 scanner is shown in Figure A.1. As can be seen from Figure A.2, a piece of smooth surface was marked with several longitudinal and transverse lines.

A.1.2 Procedures

- Use the scanner to scan the smooth surface as shown in Figure A.1 and save the data.
- Turn the scanner by 180° , scan the smooth surface again, and save the data.
- Since the piece of surface is smooth and leveled, the elevation of each line should be the identical. If the elevations of any line are different, it means some errors involved. The elevations are needed to be corrected.



Figure A.1: The line-laser scanner used in this thesis.

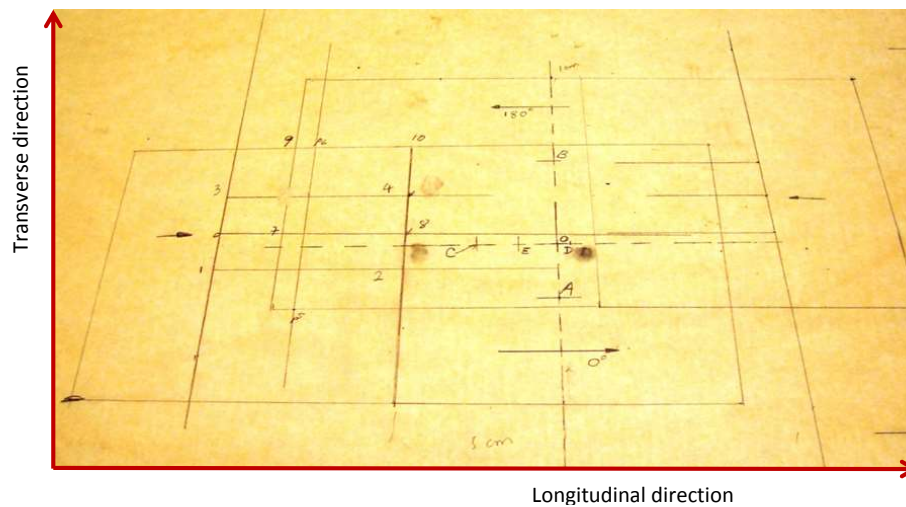


Figure A.2: A piece of smooth surface marked with longitudinal and transverse lines.

A.1.3 Longitudinal Calibration

Figure A.3 is the image of the smooth surface including line78 from the scanner, while Figure A.4 is the image of the smooth surface including line78 when the scanner was turning 180°.

Take the profile of line78 as an example to investigate the trend in longitudinal direction. Figure A.5 shows the profile of line78 from the scanner, while Figure A.6 is the the profile of line78 when the scanner was turning 180° which is named as line78-180°.

As can be seen from Figure A.7 , the profile becomes flat when profile of line78-180° is added to profile of line78. From this observation, it can be concluded that the line78 of the smooth surface itself is flat, but the scanner has a slope (systematic error) along the longitudinal direction. The slope was found at $Slope_{78} = 1.3044 \times 10^{-04}$ by doing regression analysis. After applying this correcting factor to the scanned profiles, the modified profile of line78 is shown in Figure A.8

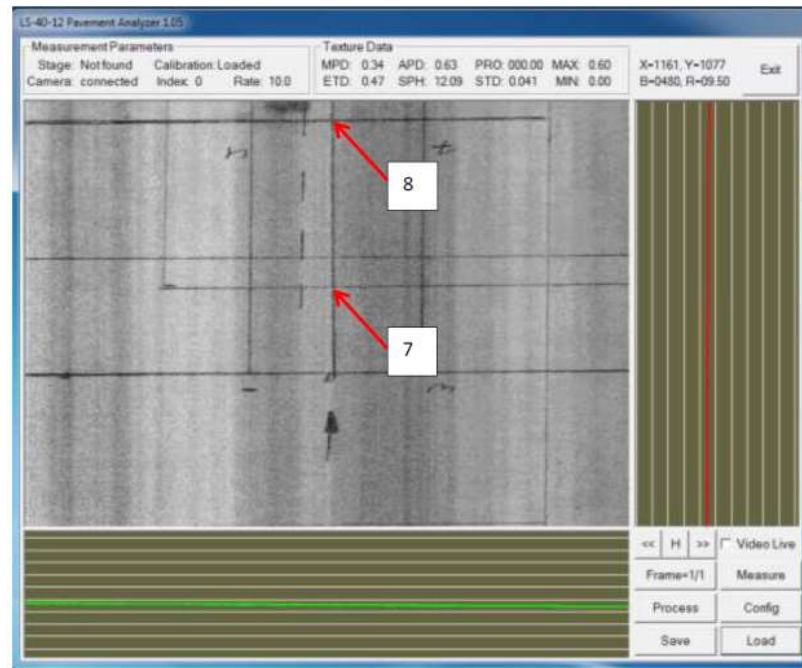


Figure A.3: An image of smooth surface including line78 from LS-40 scanner.

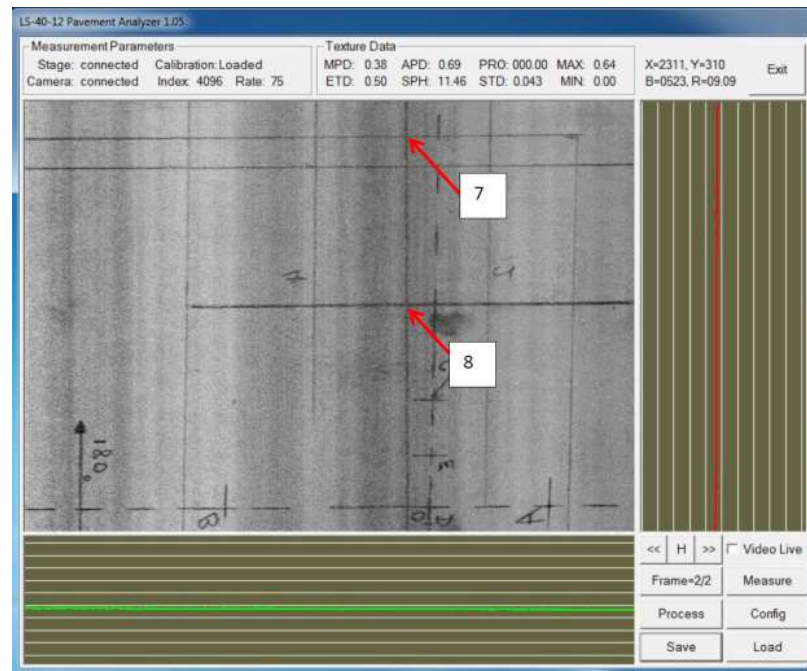


Figure A.4: An image of smooth surface including line78 from LS-40 scanner with 180° turning.

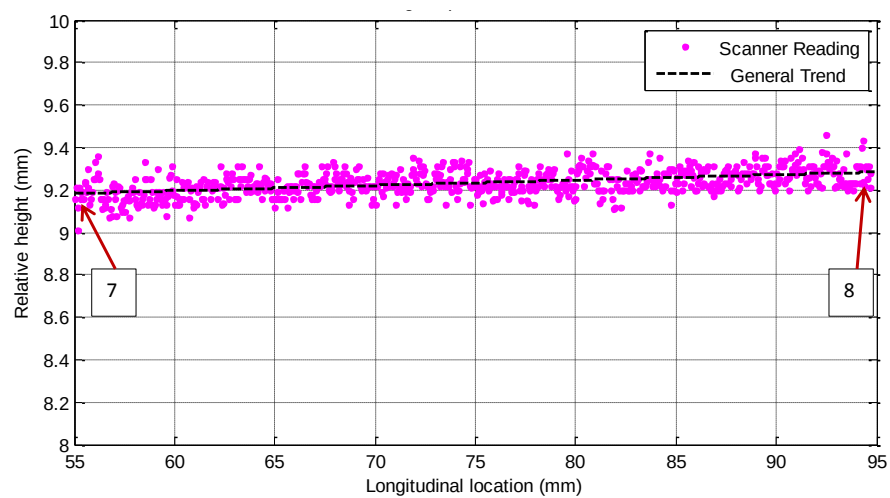


Figure A.5: The profile of line78.

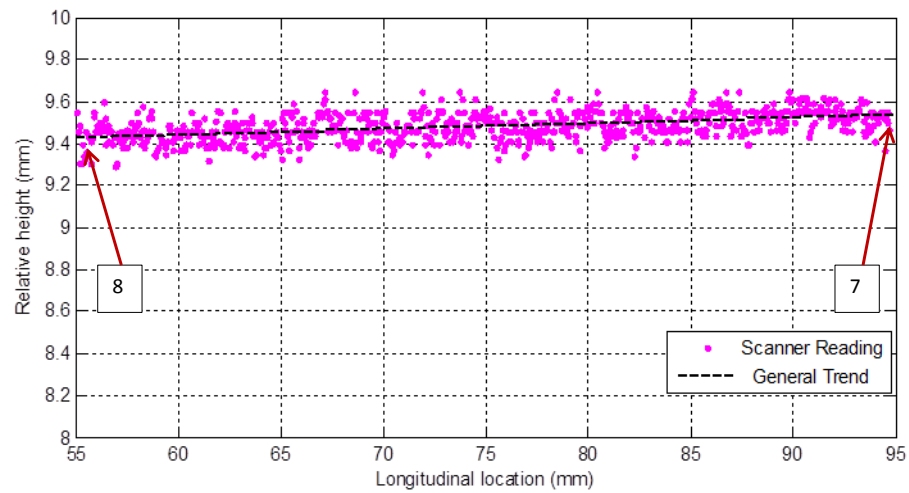
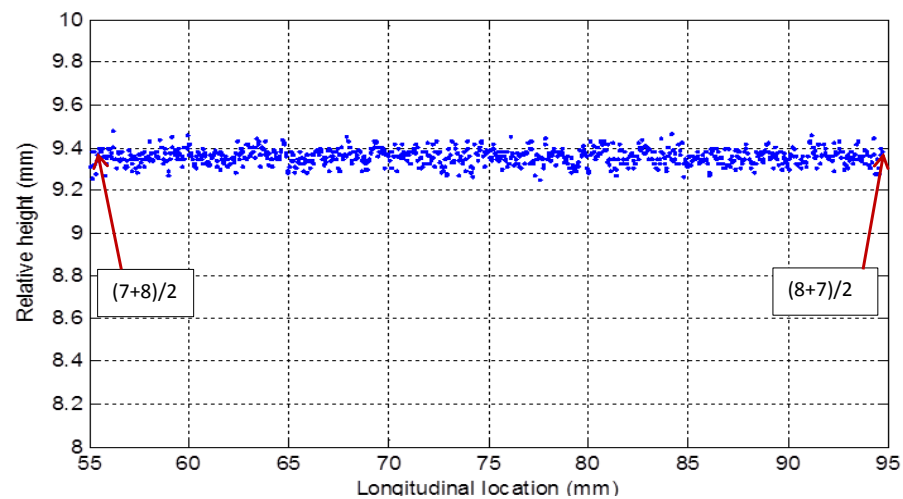


Figure A.6: The profile of line78-180°.

Figure A.7: The profile of $(\text{line78}+\text{line78-180}^\circ)/2$.

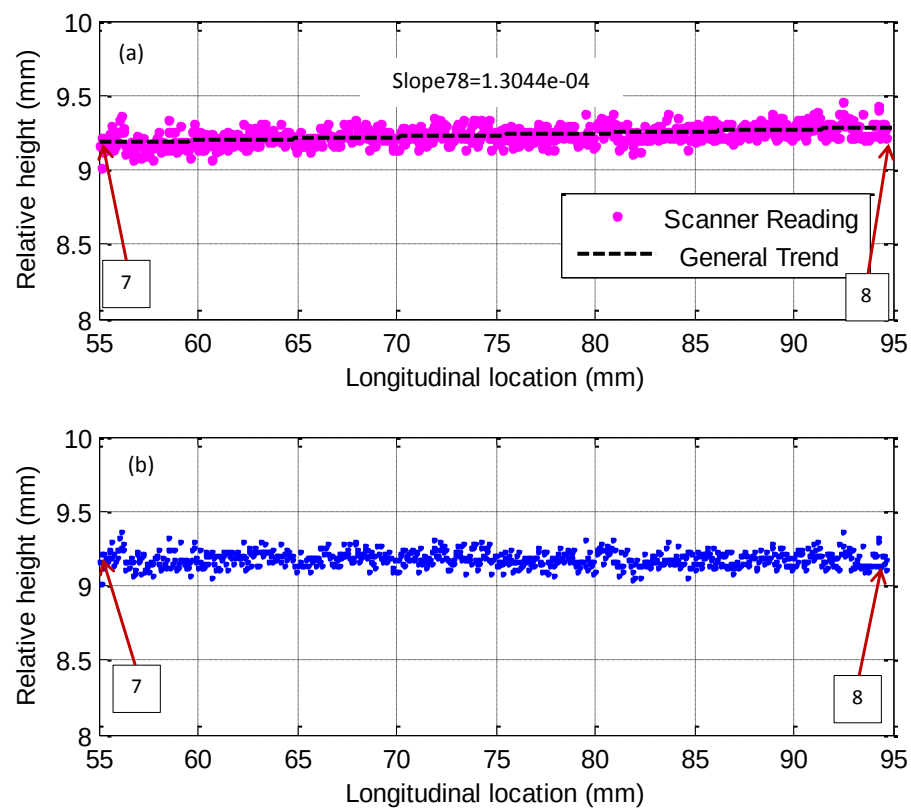


Figure A.8: Longitudinal profile and calibration (a) original profile of line78 (b) calibrated profile of line78.

A.1.4 Transverse Calibration

The transverse calibration was carried out by using the similar approach as longitudinal calibration as mentioned in the previous section.

Take the profile of lineAB in Figure A.2 as an example to explore the trend in transverse direction. Figure A.9 shows the profile of lineAB from the scanner, while Figure A.10 is the profile of lineAB when the scanner was turning 180° which is denoted as lineAB- 180° .

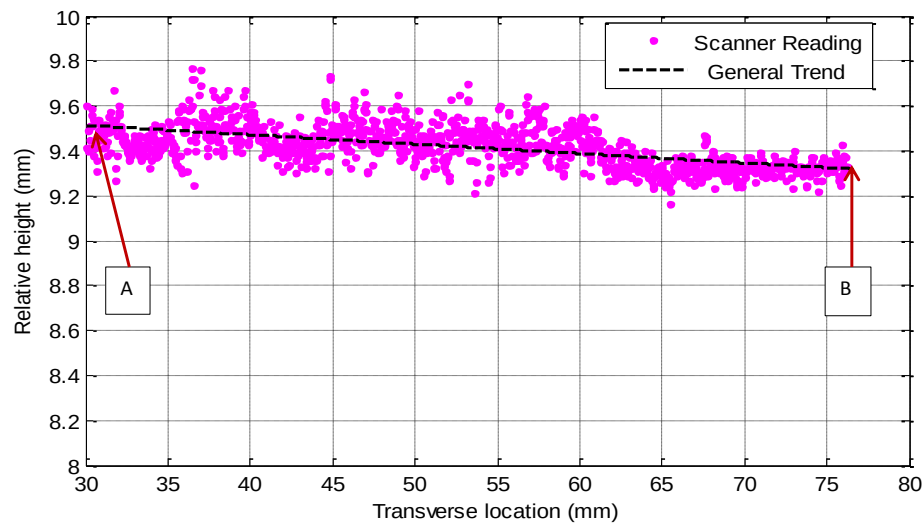


Figure A.9: The profile of lineAB.

As can be seen from Figure A.11, the profile becomes almost flat when profile of lineAB- 180° is added to the profile of lineAB. From this observation, it can be concluded that the lineAB of the smooth surface itself is flat, but the scanner has a slope (systematic error) along the transverse direction. The slope was found at $Slope_{AB} = -1.2652 \times 10^{-04}$ by doing regression analysis. After applying this correcting factor to the scanned profiles, the modified profile of lineAB is shown in Figure A.12

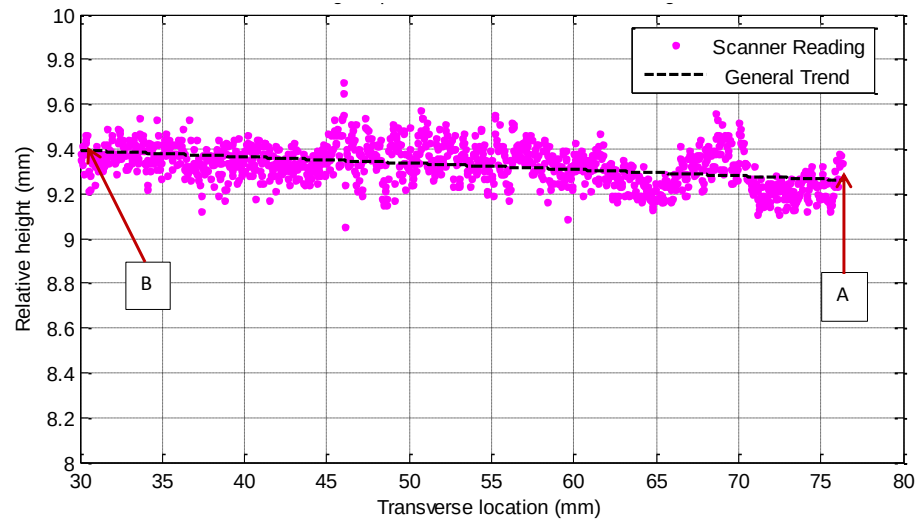


Figure A.10: The profile of lineAB-180°.

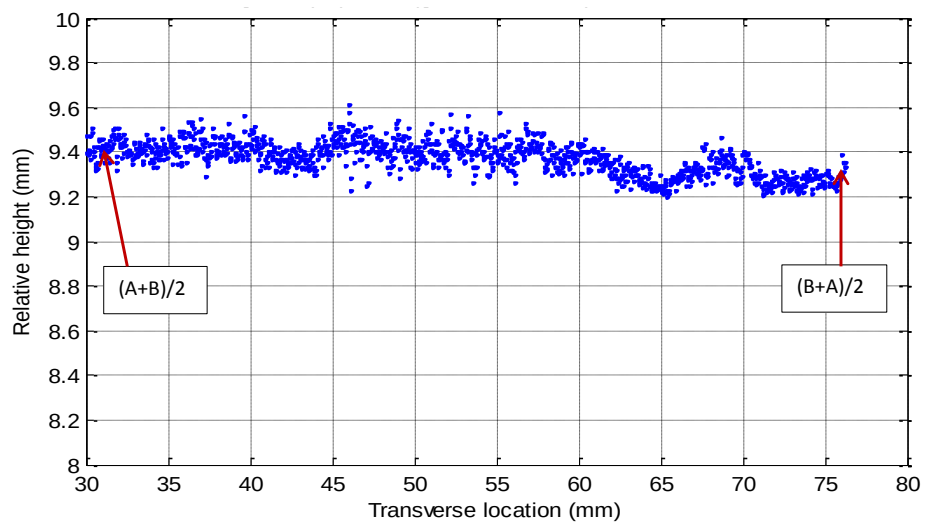


Figure A.11: The profile of $(\text{lineAB} + \text{lineAB-180}^\circ)/2$.

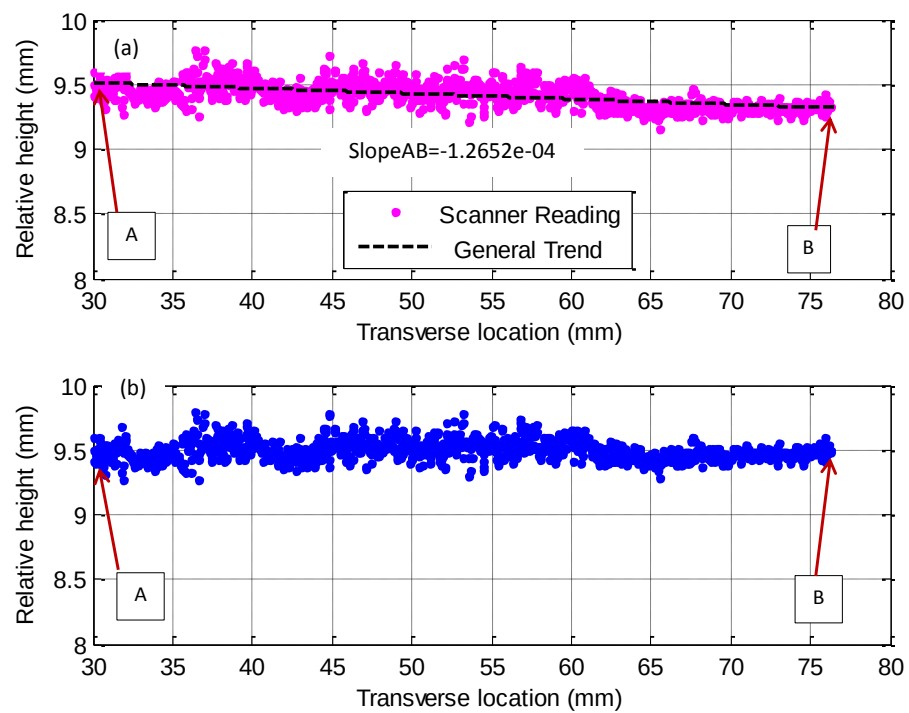


Figure A.12: Transverse profile and calibration (a) original profile of lineAB (b) calibrated profile of lineAB.

A.2 Vertical Error Distribution and Its Calibration

Vertical calibration was carried out after horizontal calibration, which means both longitudinal and transverse calibration factors were applied to the scanned profiles before vertical calibration.

The vertical measurement limit of the line-laser scanner is from -4.50 to 14.50 mm. The reading at the bottom edge (top of the smooth surface) is about 9.00 mm as shown in Figure A.13, the up limit is 14.5 mm, and the down limit is -4.50 mm at current settings.



The reading at the bottom of the scanner's edge (the top of the plywood) is about 9.00 mm. The up limit is 14.50 mm, and the down limit is -4.50 mm.

Figure A.13: Vertical measurement limit of the line-laser scanner.

A.2.1 Calibration Tools

The devices and tools used in vertical calibration are: LS-40 scanner, a piece of smooth surface, and various calibration blocks or gauges as shown in Figure A.14. The piece of smooth surface was used as a basis on which the LS-40 scanner was sat. The thickness of

each reference block is 12.5 mm, while the thickness of each calibration block is 3 mm. The thicknesses of the steel gauges are 1.72, 2.76, 3.31, 5.21, 6.48, 7.75, and 12.83 mm.

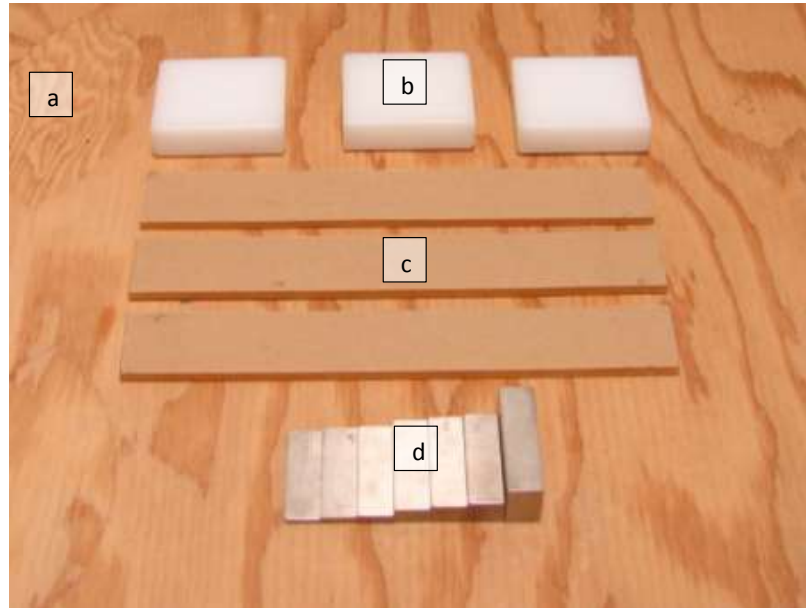


Figure A.14: Tools for vertical calibration (a) piece of smooth surface (b) reference blocks (c) calibration blocks (d) steel gauges.

A.2.2 Procedures and Data Analysis

1. As shown in Figure A.15, the line-laser scanner was sat on the top of a smooth surface with various blocks were inserted under the bottom edge of the scanner. Steel gauges were put inside the scanner and the heights of the gauges were scanned and saved.
2. The scanned files were opened by using Matlab. Longitudinal and transverse calibrations were applied. The results for various tests were shown in Table A.1.
3. The relationship between the scanner readings and the calculated unit error were analyzed and was shown in Figure A.16.
4. As can be seen from Figure A.16, the zero unit error was found at reading of 9.65

mm. This observation indicates that there is no vertical error if the scanner reading is 9.65 mm after horizontal correction.

5. The total errors were re-calculated and plotted as shown in Figure A.17.

A.3 Summary of Calibration Procedure

In summary, the calibration processes for the line-laser scanner are as follows:

1. Scan and save the surface profile using the line-laser scanner.
2. Carry out longitudinal correction by applying calibration factor of 1.3044×10^{-04} to each reading.
3. Carry out transverse correction by applying calibration factor of -1.2652×10^{-04} to each reading.
4. The updated surface elevations were represented by Z_{xy} after steps of 2 and 3.
5. Carry out vertical correction by applying calibration factor of $-0.7620 - 0.1781Z_{xy} + 0.0101Z_{xy}^2$ to each reading.
6. Finish the calibration.

As an example, Figure A.18 shows a set of steel gauges and their relative elevations of the central line.

A.4 Verify Calibration Effects

To check the effect of this calibration of the line-laser readings, a set of steel gauges shown in Figure A.18 (a) were put under the scanner in two directions perpendicular to each other.

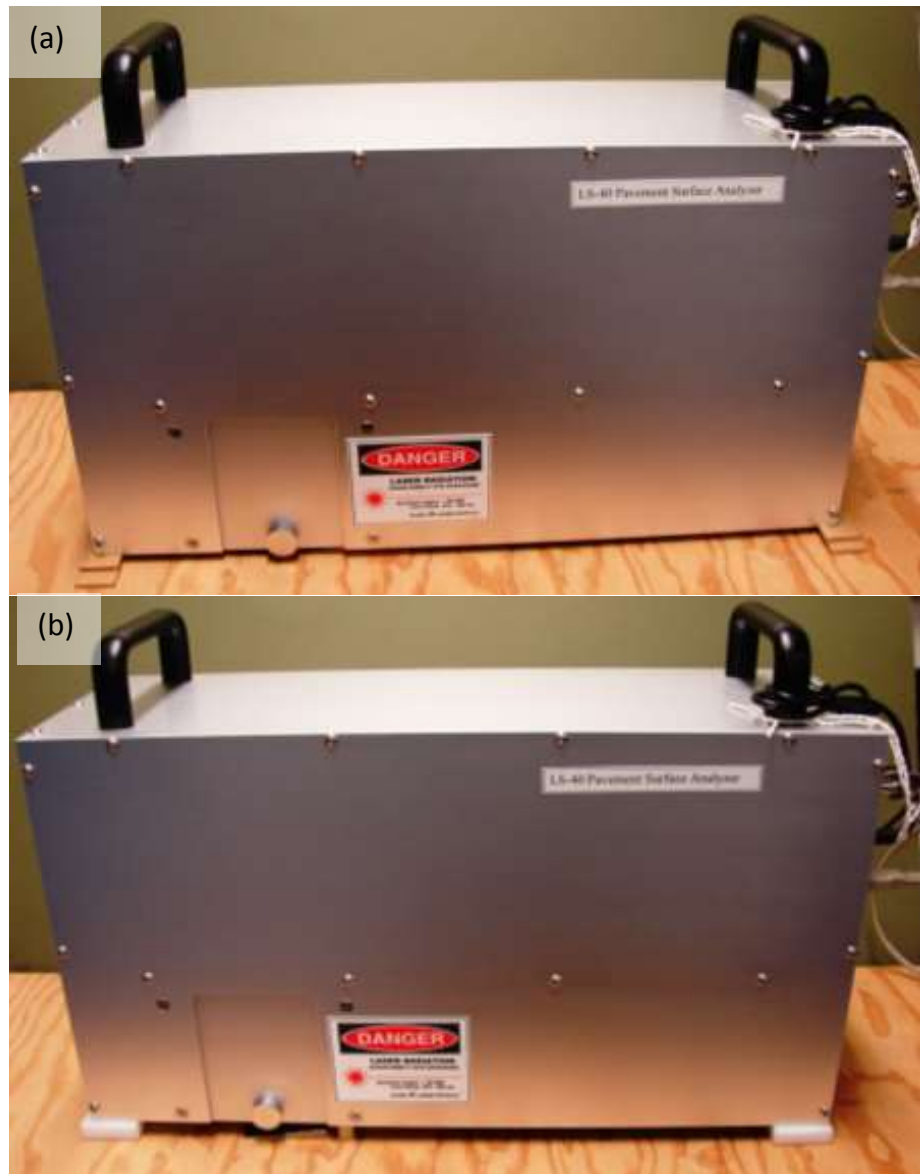


Figure A.15: LS-40 scanner sat on smooth surface with various blocks inserted underneath
(a) 6 mm block inserted (b)) 12.5 mm block inserted.

Table A.1: Test results with various blocks inserted under the scanner.

Scanner reading after horizontal calibration	Normalized reading (Assume 1 st reading=0)	Standard deviation	Steel gauge thickness	Relative total error	Step error	Unit error
(2)	(4)	(5) = (2) - (4)	(6) = (5) ⁱ⁺¹ - (5) ⁱ	(7) = $\frac{(5)^{i+1} - (5)^i}{(4)^{i+1} - (4)^i}$		
11.93	2.78	0.10	2.67	0.11	0.08	0.08
12.64	3.50	0.10	3.31	0.19	0.08	0.13
14.60	5.46	0.03	5.21	0.25	0.06	0.03
7.75	1.62	0.07	1.72	-0.10	-0.10	-0.06
8.73	2.61	0.07	2.67	-0.07	0.03	0.04
9.39	3.26	0.07	3.31	-0.05	0.02	0.03
11.35	5.22	0.08	5.21	0.00	0.05	0.03
12.73	6.60	0.11	6.48	0.12	0.11	0.09
14.07	7.94	0.13	7.75	0.19	0.07	0.06
6.79	1.65	0.07	1.72	-0.07	-0.07	-0.04
7.70	2.56	0.06	2.67	-0.11	-0.04	-0.04
8.35	3.21	0.07	3.31	-0.09	0.02	0.03
10.27	5.13	0.07	5.21	-0.08	0.01	0.01
11.59	6.45	0.07	6.48	-0.03	0.05	0.04
12.95	7.81	0.09	7.75	0.06	0.09	0.07
4.83	1.56	0.06	1.72	-0.16	-0.16	-0.09
5.73	2.45	0.07	2.67	-0.22	-0.06	-0.06
6.33	3.05	0.06	3.31	-0.25	-0.03	-0.05
8.17	4.90	0.09	5.21	-0.31	-0.06	-0.03
9.46	6.18	0.08	6.48	-0.30	0.01	0.01
10.74	7.46	0.11	7.75	-0.29	0.01	0.01
3.89	1.52	0.05	1.72	-0.19	-0.19	-0.11
4.77	2.41	0.06	2.67	-0.26	-0.07	-0.07
5.37	3.01	0.06	3.31	-0.30	-0.03	-0.05
7.19	4.83	0.05	5.21	-0.38	-0.08	-0.04
8.43	6.07	0.06	6.48	-0.41	-0.04	-0.03
9.69	7.33	0.06	7.75	-0.42	-0.01	-0.01
2.05	1.47	0.05	1.72	-0.25	-0.25	-0.14
2.88	2.30	0.05	2.67	-0.37	-0.12	-0.13
3.47	2.89	0.05	3.31	-0.41	-0.04	-0.06
5.17	4.59	0.05	5.21	-0.62	-0.21	-0.11
6.39	5.81	0.05	6.48	-0.67	-0.06	-0.04
7.61	7.03	0.05	7.75	-0.72	-0.04	-0.03
12.81	12.23	0.08	12.83	-0.60	0.12	0.02
1.16	1.40	0.05	1.72	-0.32	-0.32	-0.19
2.00	2.24	0.05	2.67	-0.43	-0.11	-0.12
2.55	2.79	0.06	3.31	-0.51	-0.08	-0.13
4.28	4.52	0.04	5.21	-0.69	-0.18	-0.09
5.41	5.65	0.05	6.48	-0.83	-0.14	-0.11
6.62	6.86	0.05	7.75	-0.89	-0.06	-0.05
11.73	11.97	0.08	12.83	-0.86	0.03	0.01
-0.63	1.40	0.06	1.72	-0.31	-0.31	-0.18
0.16	2.20	0.05	2.67	-0.48	-0.16	-0.17
0.70	2.73	0.05	3.31	-0.58	-0.10	-0.16
2.30	4.33	0.05	5.21	-0.88	-0.30	-0.16
3.45	5.49	0.07	6.48	-0.99	-0.12	-0.09
4.60	6.63	0.07	7.75	-1.12	-0.13	-0.10
9.49	11.52	0.07	12.83	-1.31	-0.19	-0.04
-1.49	1.35	0.07	1.72	-0.37	-0.37	-0.21
-0.71	2.12	0.05	2.67	-0.55	-0.18	-0.19
-0.18	2.65	0.06	3.31	-0.65	-0.11	-0.17
1.41	4.25	0.06	5.21	-0.96	-0.31	-0.16
2.51	5.35	0.06	6.48	-1.13	-0.17	-0.13
3.63	6.47	0.06	7.75	-1.28	-0.15	-0.12
8.42	11.26	0.05	12.83	-1.57	-0.29	-0.06
-2.36	1.77	0.05	2.67	-0.91	-0.21	-0.22
-1.83	2.29	0.06	3.31	-1.02	-0.11	-0.17
-0.30	3.83	0.06	5.21	-1.39	-0.37	-0.19
0.77	4.89	0.05	6.48	-1.59	-0.20	-0.16
1.85	5.98	0.06	7.75	-1.77	-0.18	-0.15
6.44	10.57	0.06	12.83	-2.27	-0.49	-0.10
-3.14	1.02	0.06	2.67	-1.65	-0.21	-0.22
-2.65	1.51	0.05	3.31	-1.79	-0.15	-0.23
-1.14	3.02	0.05	5.21	-2.19	-0.40	-0.21
-0.09	4.08	0.05	6.48	-2.40	-0.22	-0.17
0.96	5.13	0.06	7.75	-2.62	-0.22	-0.17
5.46	9.63	0.04	12.83	-3.20	-0.58	-0.11

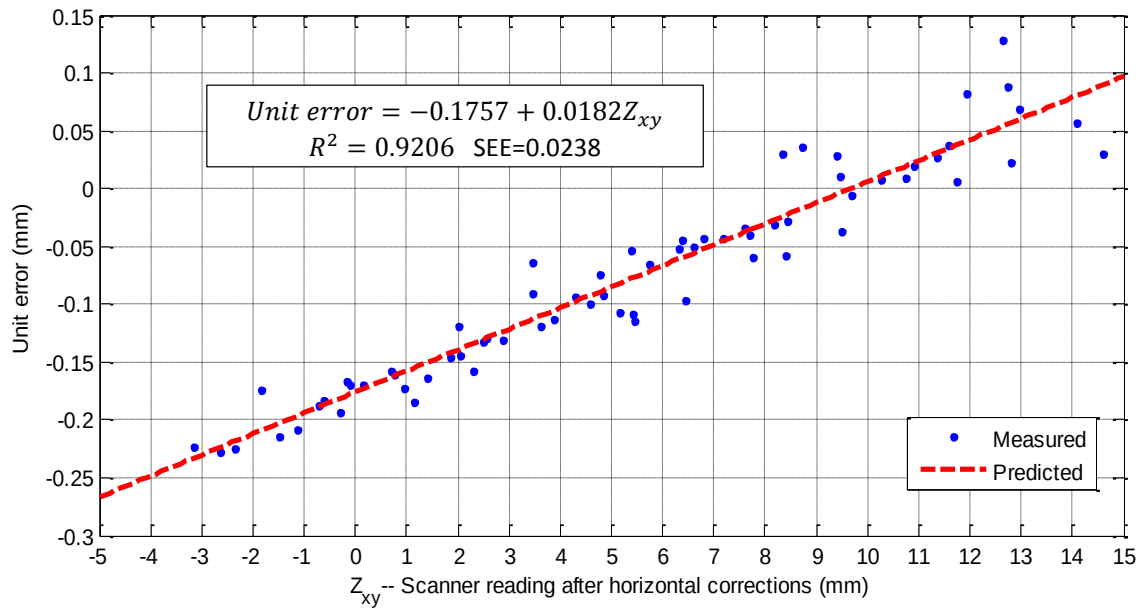


Figure A.16: Relationship between unit error and readings after horizontal correction.

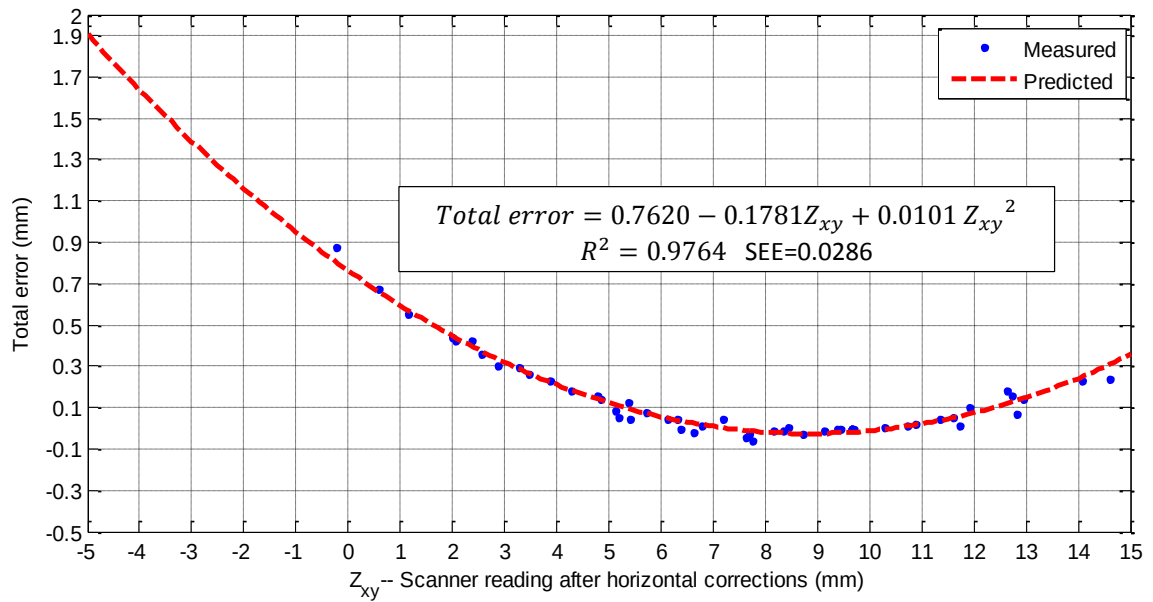


Figure A.17: Relationship between total error and readings after horizontal correction.

The recovered thickness of the steel gauges based on original readings and the calibrated heights are shown in Figures A.20 and Figure A.19.

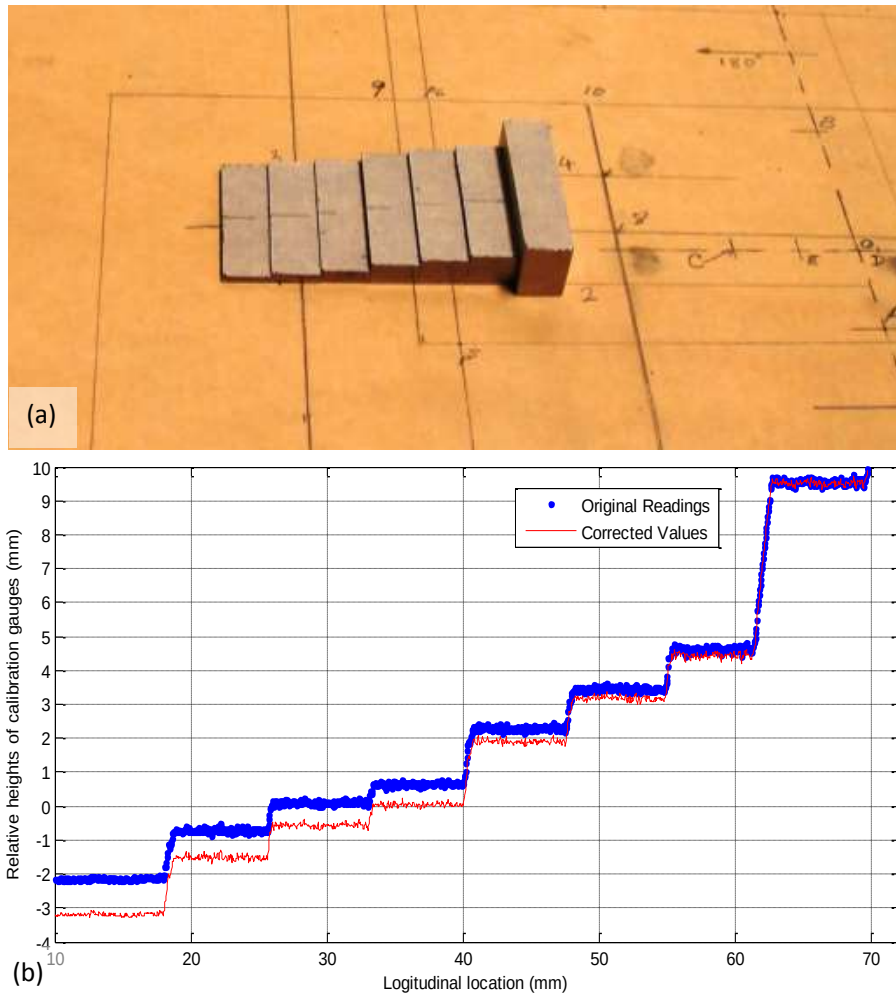


Figure A.18: Steel gauges and their recovered relative heights of the central line (a) an image of steel gauges (b) relative heights of steel gauges' central line.

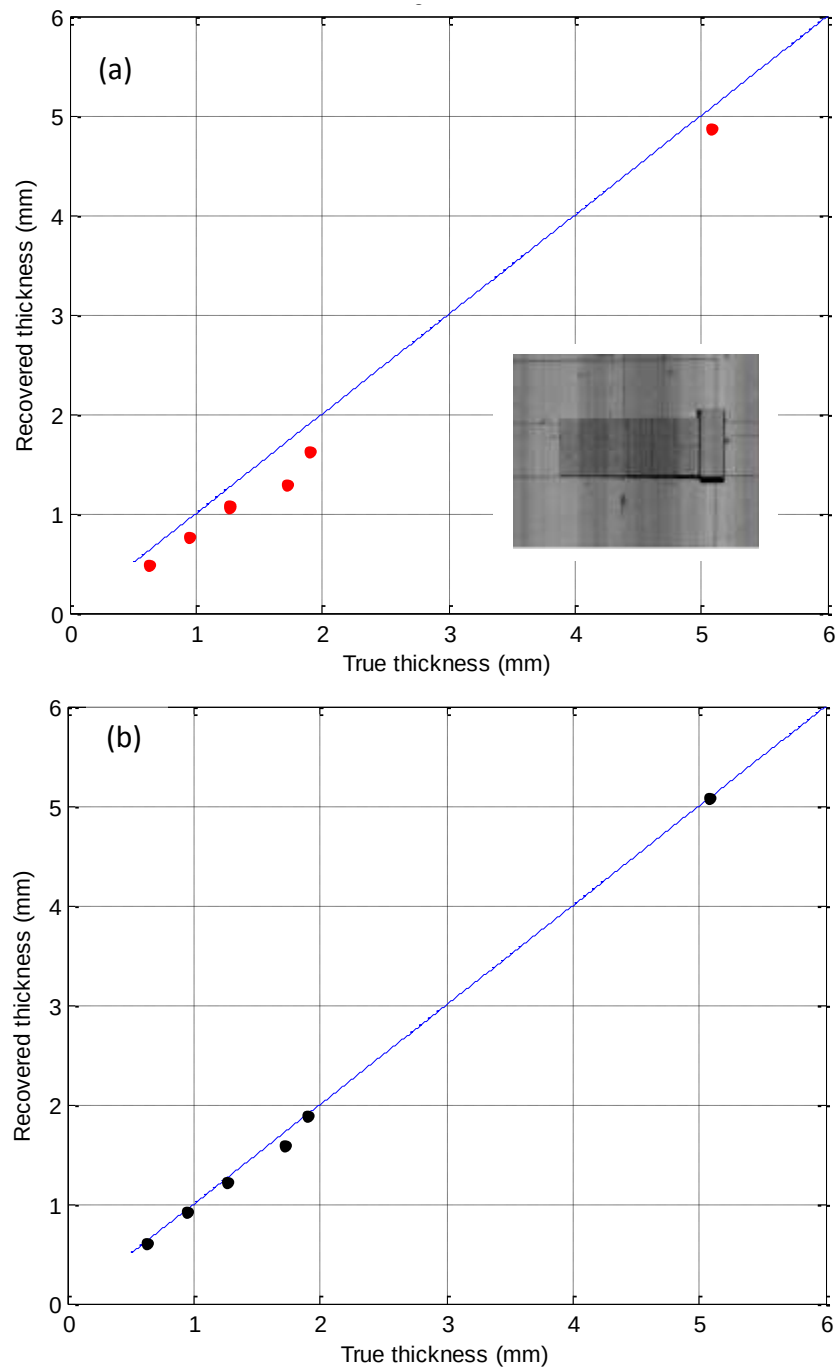


Figure A.19: Recovered steel gauges (longitudinal direction) thickness (a) original readings (b) after calibration.

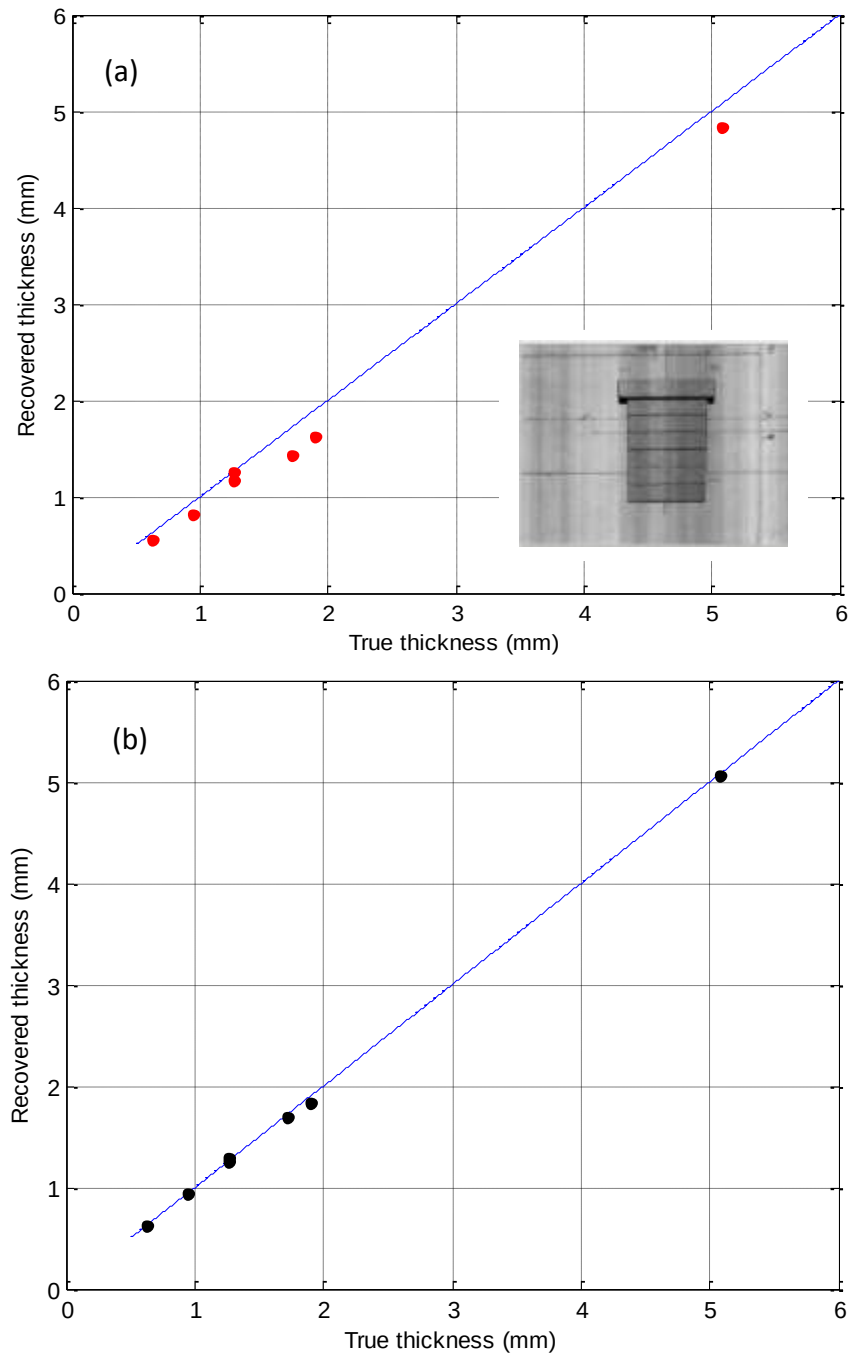


Figure A.20: Recovered steel gauges (transverse direction) thickness (a) original readings (b) after calibration