Concrete Pavement Texture and Optimizing Functional Performance

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Abstract

Concrete pavement texture is defined by the irregularities on a concrete pavement surface that deviate from an ideal, perfectly flat surface. Texture influences many aspects of road safety and comfort, including friction, smoothness, splash & spray, rolling resistance, and numerous others. The focus of this paper is on techniques to measure and analyze texture, particularly that which influences tire-pavement noise and friction. Standards for characterizing texture geometrically are described, and techniques that describe texture in terms of its influence on functional performance are explored.

Introduction

Pavement texture is defined by the irregularities on a pavement surface that deviate from an ideal, perfectly flat surface (ASME 2009). As shown in Figure 1, the World Road Association (PIARC) has established standard categories of texture, classified by wavelength. These categories include microtexture (wavelengths up to 0.5 mm), macrotexture (0.5 to 50 mm), megatexture (50 to 500 mm), and roughness (wavelengths larger than 500 mm). Texture influences many aspects of road safety and comfort, including friction, smoothness, splash & spray, rolling resistance, and numerous others. Figure 1 also illustrates the ranges of texture that influence these pavement surface characteristics, with a positive influence shown in green and deleterious effect shown in red. The focus of this paper is on techniques to measure and analyze texture, particularly that which influences tire-pavement noise and friction.

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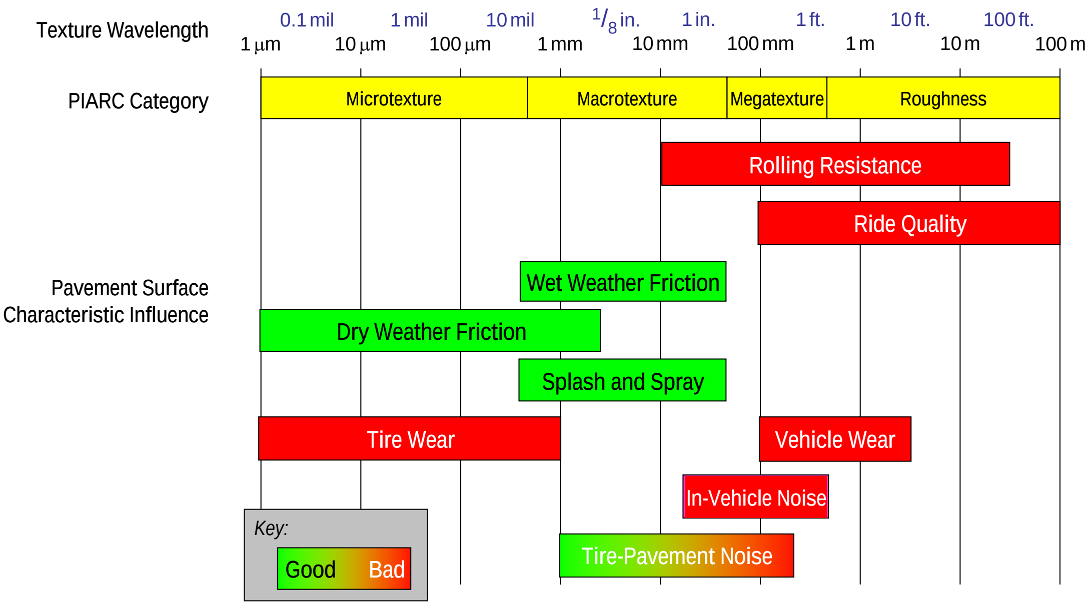

Figure 1. World Road Association (PIARC) texture definitions and their influence on pavement surface characteristics.

In modern concrete pavement construction, texture is deliberately imparted in a reasonably controlled manner. The nominal geometry of the texture is typically prescribed, either directly or indirectly. For example, as illustrated in Figure 2, the spacing and depth of the directional striations produced by tining are often described in a specification. Diamond ground textures will be defined in large part by the geometry of the grinding head (blade widths and spacers). Even the texture of a drag surface will be defined to some degree by the specific mechanical means used to impart these surfaces.

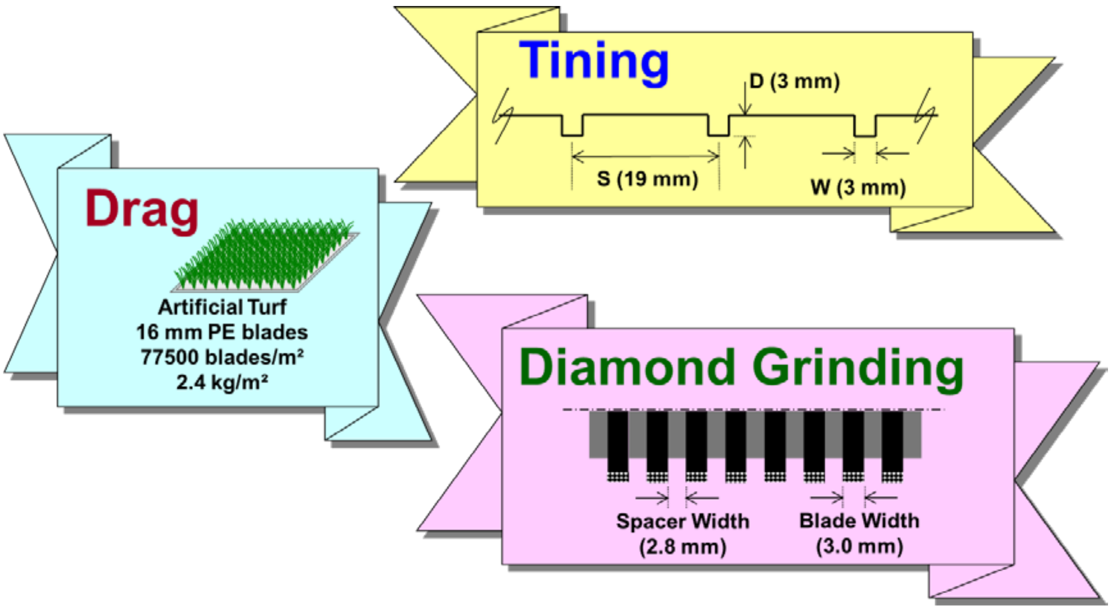

Figure 2. Typical texture specifications.

While it would be ideal for the as-constructed texture to match the as-designed (nominal) geometry, this is not usually the case. Numerous factors will affect the final texture, including variability in materials and construction technique. This is illustrated in Figure 3, which shows variability of pavement texture on two areas of a project that were constructed within minutes of each other. In addition to initial variability, texture will change over time due to both traffic and the environment.

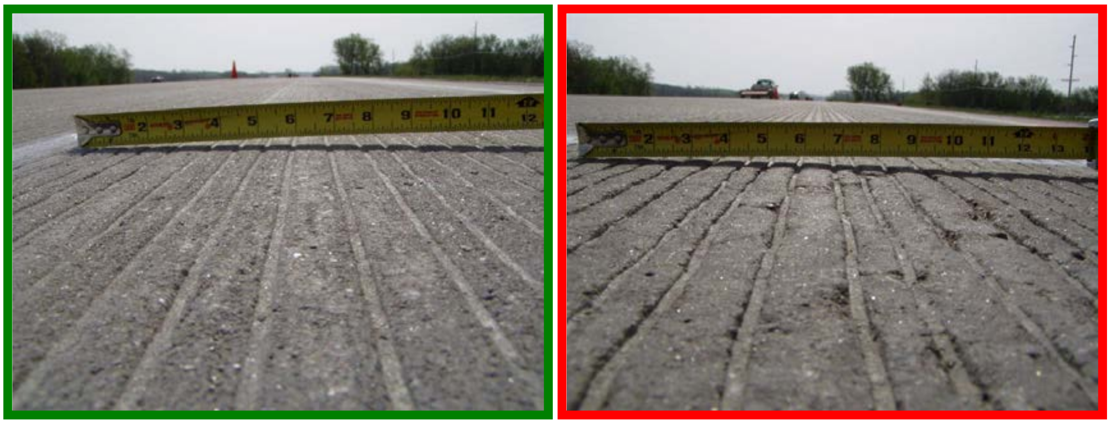

Figure 3. Material and Construction Variability affecting the As-Constructed Texture.

With texture affecting so many different surface characteristics, it is an ideal parameter to be evaluated as part of construction quality control. Furthermore, since texture is simply geometry, it is a fundamental aspect of a pavement surface to measure. This paper discusses pavement texture measurement, with specific discussion of the methods used in the Concrete Pavement Surface Characteristics Program (CPSCP) conducted by the National Concrete Pavement Technology Center (CP Tech Center). The methods and metrics used to quantify texture are also described herein.

Measuring Texture

Laser-based profilometry is the most commonly used technique to collect pavement texture data. Various standards have been developed to describe the requisite equipment in such a way that is relevant to the type of texture to be measured. Of these, ISO 13473 is the most commonly cited. While other texture measurement methods have been advanced, they often possess technical or practical limitations. Laser-based texture profilometry uses technology that is similar to road profilers that evaluate pavement smoothness. However, when measuring texture, a greater degree of precision and accuracy is needed with respect to small features that are normally filtered out when evaluating road roughness.

Most profilers in use today measure texture using a single point laser which results in a 2-dimensional (2-D) texture profile; distance along the pavement surface as one dimension, and the texture elevation as the second. Concrete pavement texture is complex though; it is anisotropic, meaning that the texture varies depending on the direction of the measurement – longitudinal or transverse. Measuring a 2-D profile therefore fails to completely describe characteristics of the texture that are important to many surface characteristics. In addition, measuring with a single point laser can introduce artifacts in the measurement that distort the profile, and thus introduce error in predicting the surface characteristic of interest.

To overcome the limitation of using a spot sensor, a line laser can be used instead. Traditionally, line lasers are found in machine vision applications. In recent years, vendors of these sensors have worked with the highway industry to develop variants of the sensors that are suitable for texture profile applications. Figure 4 illustrates the measurement principle of a line laser. Measuring with a line laser results in a 3-dimensional (3-D) texture profile; distance along the pavement surface as one dimension, distance along the laser line as the second dimension, and texture elevation as the third.

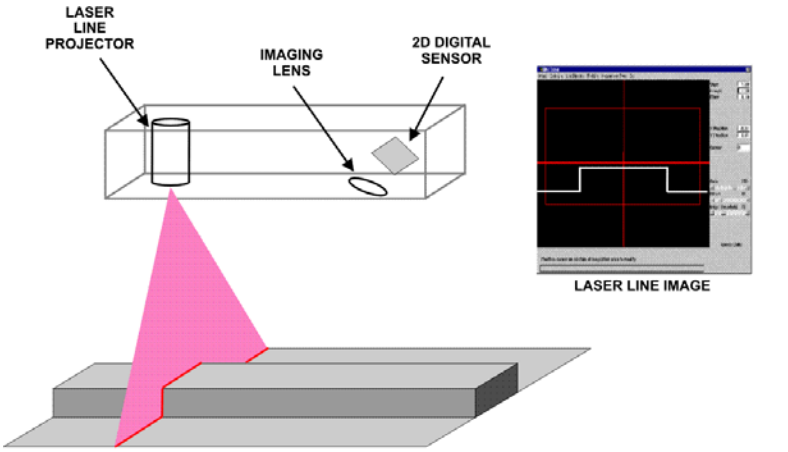

Figure 4. Measurement principle of LMI-Selcom RoLine line laser height sensor.

RoboTex

A line laser sensor alone cannot measure pavement texture properly. A platform with a means to mobilize the sensor is required. In 2005, a prototype of an innovative system for texture measurement was developed: a robotic-based texture measurement system (RoboTex) (Rasmussen 2007). As shown to the left of Figure 5, the system is built on a robotic chassis for remote control of the speed and direction of travel of the measurement platform.

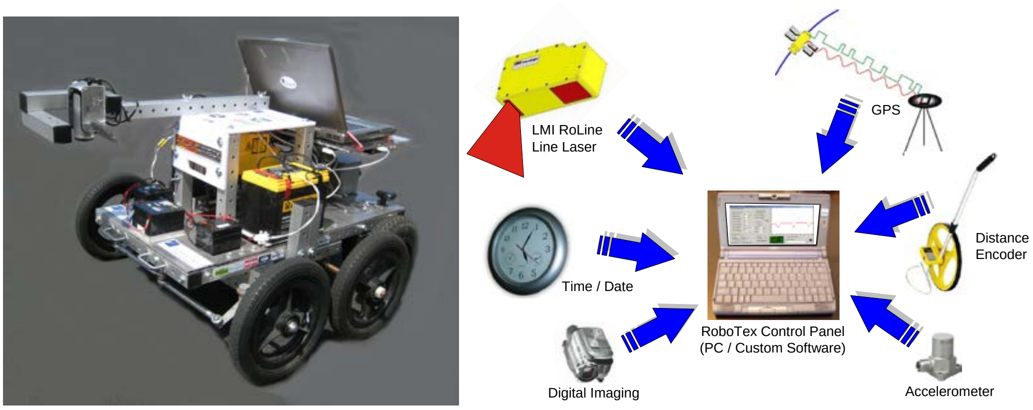

Figure 5. RoboTex texture measurement system photo (left),
and schematic of components (right).

RoboTex includes customized software that simultaneously collects and stores data from a number of sensors. As illustrated to the right of Figure 5, these include:

- Line laser sensor – for height data;
- Accelerometer – to establish an inertial reference elevation;
- Wheel encoder – to determine the precise position of the robot;
- GPS – to establish a global position of the robot for reference;
- Time – to determine speed and for global reference; and
- Digital imaging system – for a visual record of the surface.

The result is a concept device that provides a better tradeoff between resolution and efficiency in texture data collection. RoboTex is capable of sampling 100 or more texture elevation points across a 100-mm wide laser line at 1000 Hz as it travels down the road under its own power at approximately 0.5 m/s. This yields a pavement texture measurement with a spatial resolution of about 0.4 mm^2, and a height resolution of 0.01 mm. More importantly, the result is a three-dimensional texture profile along a 100-mm wide swath of pavement surface, as illustrated in Figure 6.

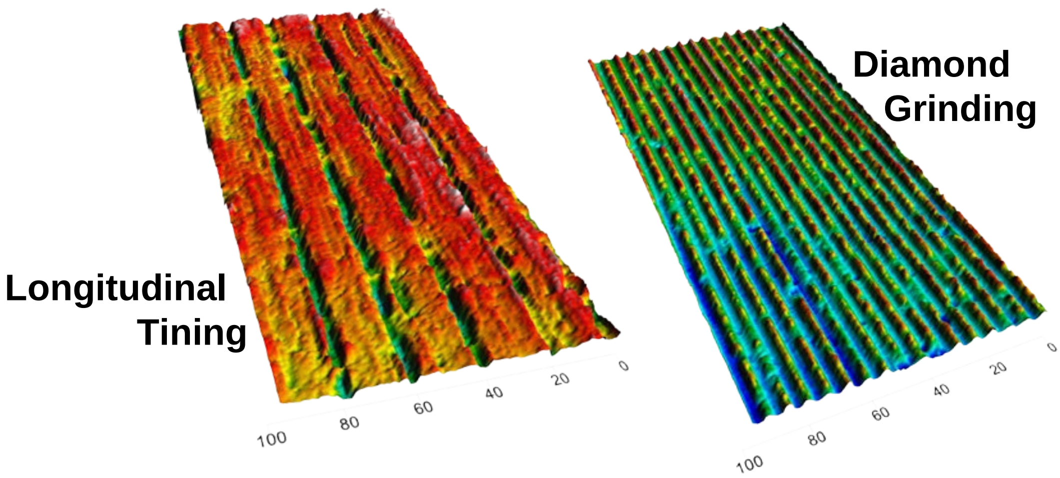

Figure 6. Sample RoboTex data from concrete pavement textures.

Geometric Texture Metrics

While illustrations of the measurements as shown in Figure 6 are useful, they do not quantify texture. However, there are a multitude of ways to characterize texture. The selection of a proper metric should begin with an understanding of the fundamental mechanisms that describe the surface characteristics of interest. Ideally, a texture metric should describe the texture in a way that relates its interaction with a tire.

Quite often, texture depth is used as a texture metric. However, there are numerous ways that texture depth can be calculated. To illustrate this, refer to a short (100 mm) sample of tined concrete pavement texture, as illustrated in Figure 7.

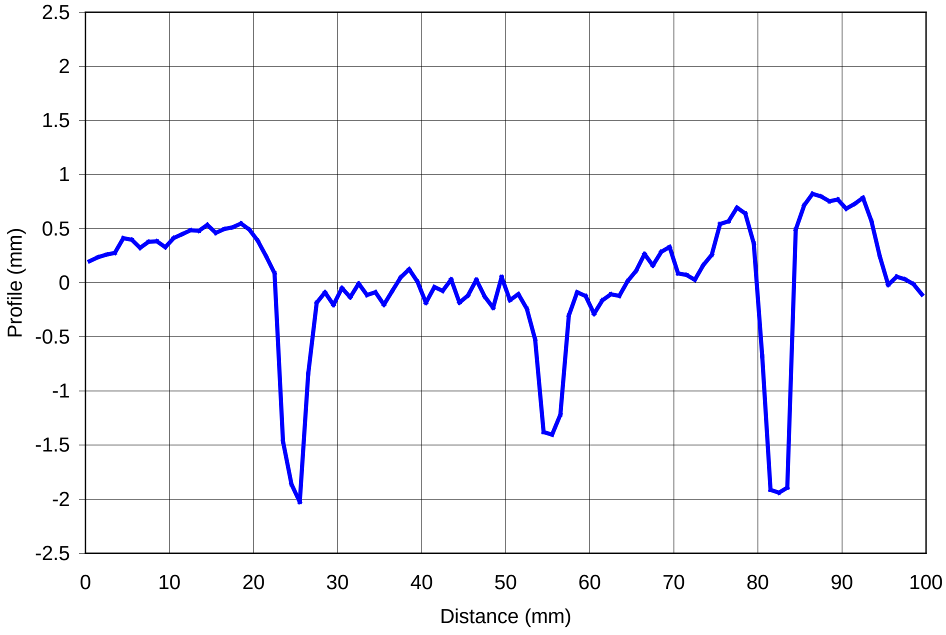

Figure 7. Sample texture profile.

A straightforward way to calculate texture depth is to calculate an average (rectified) deviation of the texture from the mean depth. This is illustrated to the top of Figure 8, where the sum of the shaded areas both above and below the mean profile elevation is divided by the length of the profile (100 mm). The result is in an average texture depth (R_a) of 0.42 mm. Alternatively, the texture profile shown in Figure 7 can be squared, as illustrated to the bottom of Figure 8. Taking this area, dividing by the length of the profile, and then taking the square root, results in the root-mean-square or rms texture depth (R_q). In this example, the rms is 0.63 mm. Mathematically, these calculations are made as follows using measured texture data:

$$R_a = \frac{\sum_{n=1}^{N} |z_n|}{N} \quad \text{and} \quad R_q = \sqrt{\frac{\sum_{n=1}^{N} z_n^2}{N}}$$

Where,

N = number of measured samples of texture profile, and

z_n = texture profile elevation data (starting with n=1, and ending with n=N) after detrending.

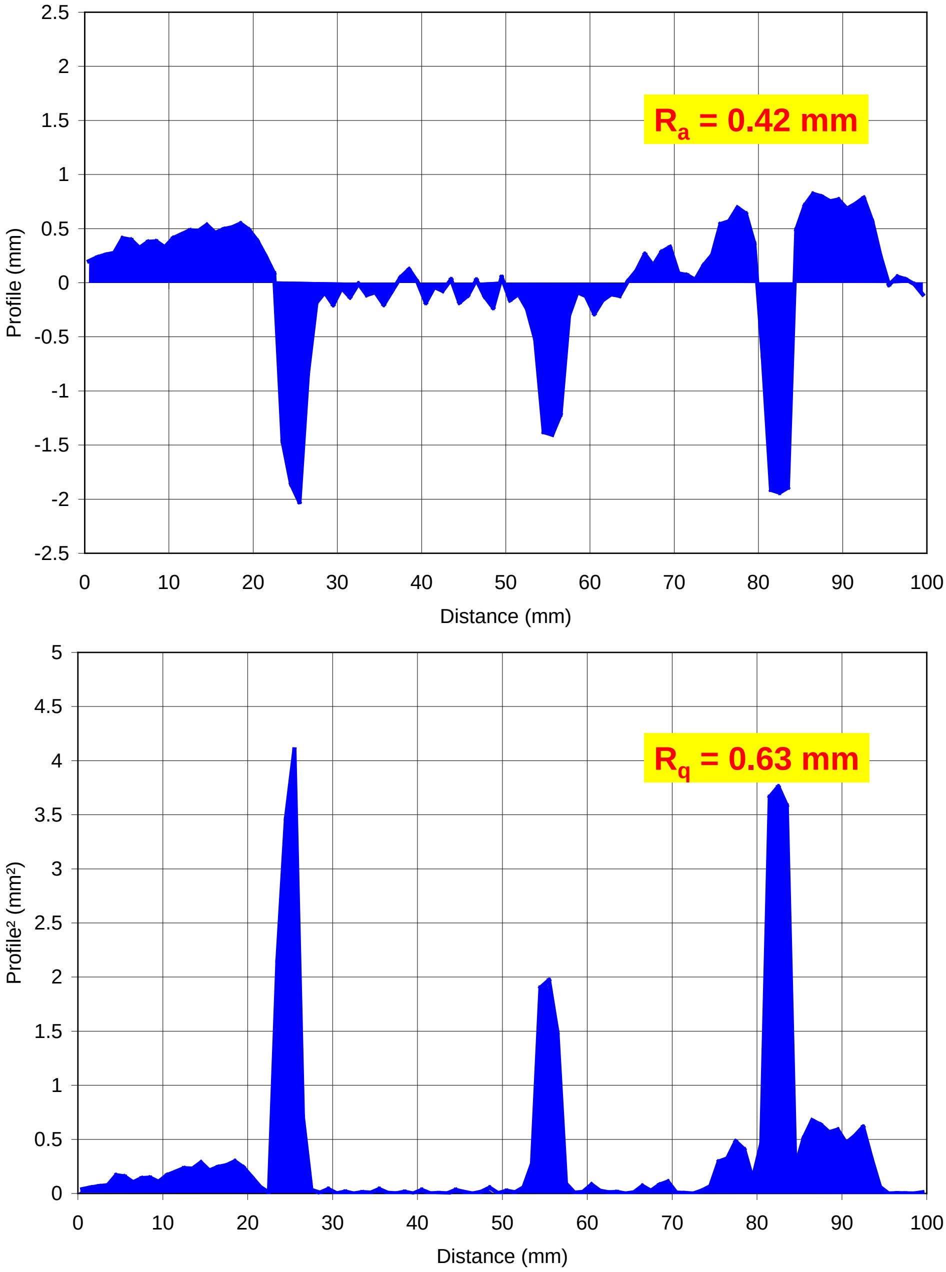

Figure 8. Calculation of Average Texture Height, R_a (top) and RMS Texture Height, R_q (bottom).

One disadvantage of most texture depth metrics is the lack of sensitivity to directionality of the texture. For example, the same R_a and R_q values are calculated for the texture profile in Figure 7 even if the profile is "flipped over" (upside down). In the flipped over case, the tined grooves become sharp spikes and clearly, a tire would interact with this profile very differently than the right-side up profile. To help overcome this limitation, a directionality metric termed texture skewness (R_{sk}), is calculated as follows:

$$R_{sk} = \frac{\sum_{n=1}^{N} z_n^3}{R_q^3 N}$$

For textures like that shown in Figure 7, the skew is negative (in this example, -1.7). If the profile is flipped over the texture has a positive skew.

Historically, pavement texture depth has been measured using the volumetric ("sand") patch technique and reported as a mean texture depth (MTD) (ASTM 2001). The test involves carefully spreading a known volume of small glass beads into a circle on the pavement surface; the MTD is simply the volume of beads divided by the area of the circle. As laser-based profilers began to be used, the mean profile depth (MPD) metric was developed as a means to estimate the MTD. As shown in Figure 9, calculating MPD involves dividing the 100 mm texture profile into two 50-mm segment halves. A peak profile point in each segment half is determined, then averaged, and then the mean profile elevation (in this case, zero) is subtracted. The result in this example is 0.69 mm. It should be noted that the currently proposed revision to the ISO 13473-1 specification refers to the calculation within a 100-mm sample as a mean segment depth (MSD); the MPD is then an average of numerous (minimum of five) MSD values.

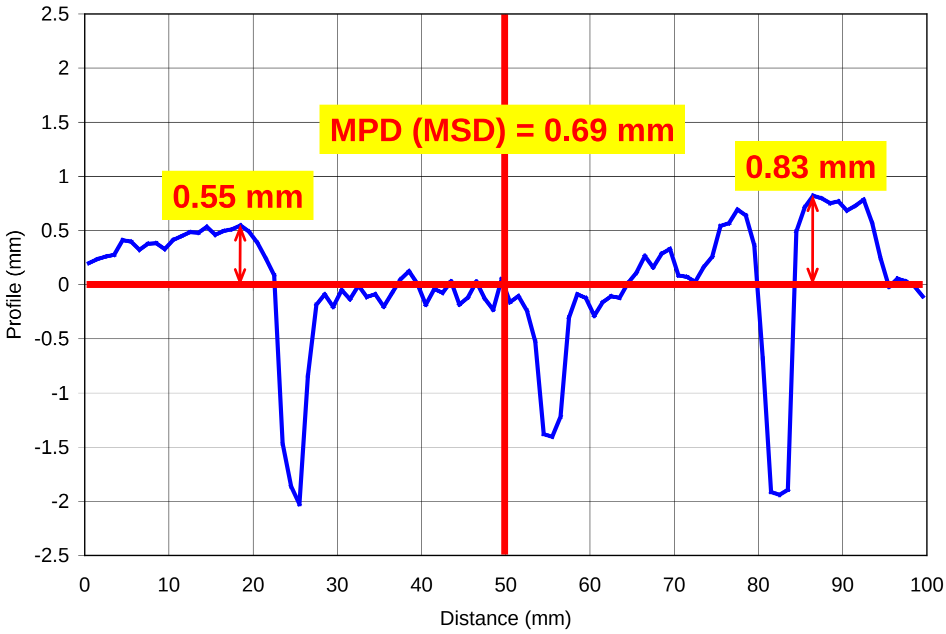

Figure 9. Calculation of Mean Profile (Mean Segment) Depth.

Functional Texture Metrics

While geometric metrics such as depth and skewness are intuitive and straightforward to calculate, by themselves they do not describe the interaction of a tire and the pavement texture. Functional texture metrics are more useful in this regard. ISO specification 13565-2 describes a process of transforming a texture profile into a profile bearing ratio curve. As illustrated in Figure 10, this begins with the recognition of three distinct "regions" of texture. The peaks are the first to be contacted by a tire, and the most rapid to wear. The second region is the core, where most of the texture typically lies, and thus describes the longevity of the texture. The lowest regions are termed valleys, and are where air and water can possibly reside that are not necessarily in contact with the tire. Calculation of the heights of these three regions first involves converting the texture profile to a Profile Bearing Length Ratio (a type of cumulative distribution of texture elevations). From this, various chord and area calculations derive the parameters of reduced peak height (R_{pk}), core roughness depth (R_k), and reduced valley depth (R_{vk}).

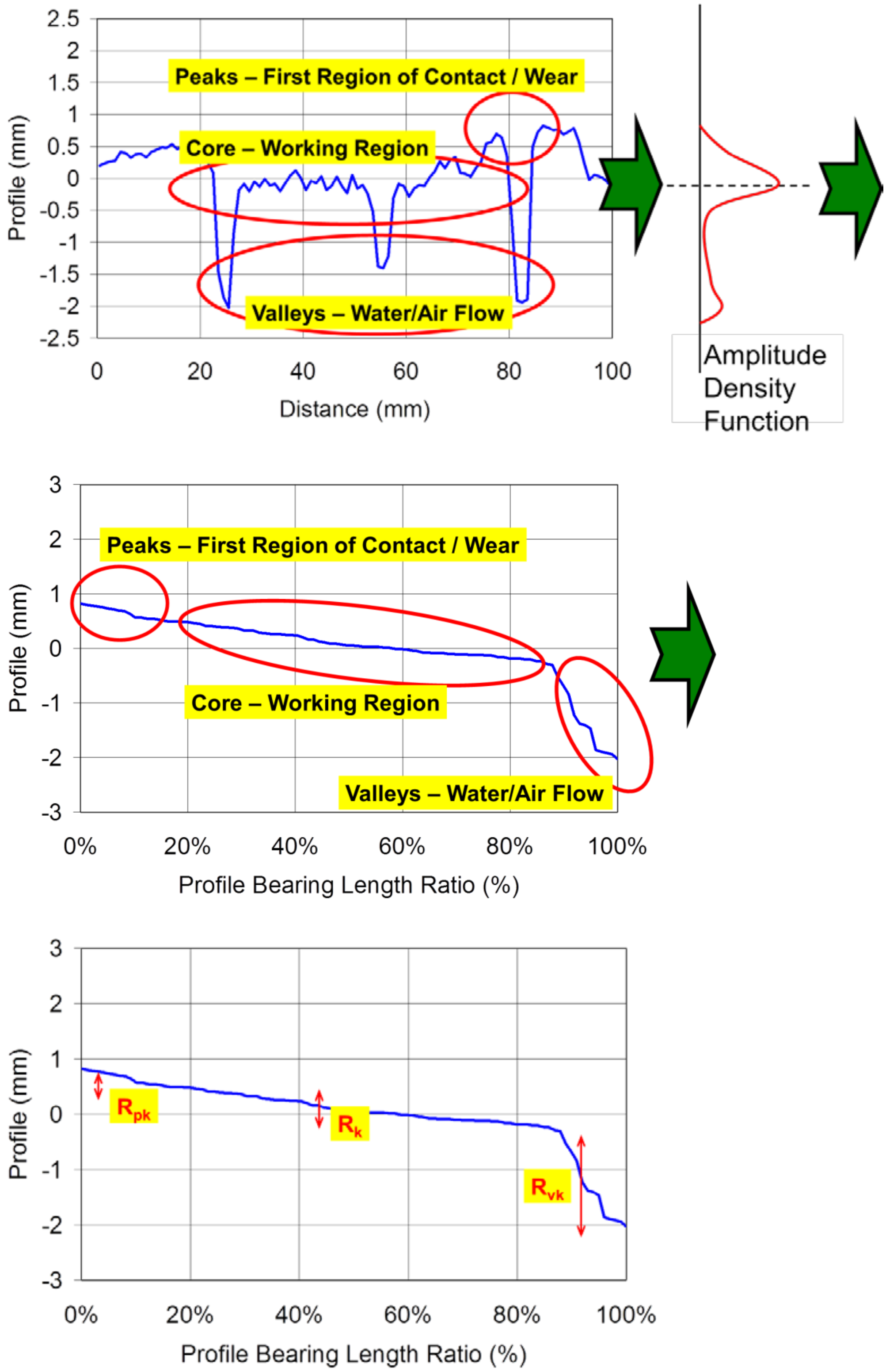

Figure 10. Calculation of Profile Bearing Ratio from a texture profile.

Spectral Texture Metrics

Spectral analysis of pavement texture is used to identify the presence or significance of various repeating features. To illustrate this, Figure 11 shows a spectral analysis of the same tined pavement shown in Figure 7. More on the technique used for this type of analysis can be found in ISO 13473-4. From this plot, a characteristic peak at 25 mm is visible, which corresponds to the tine spacing. Other less obvious characteristics of the texture can sometimes be derived from spectral analyses, particularly when the texture wavelength is plotted in narrow band (as opposed to third-octave, illustrated here). Furthermore, there is often a correlation between some pavement surface characteristics and the texture content within select spatial frequency bands (or texture wavelengths). It should also be noted that in Figure 11, a transformation of the texture elevation has been made to a texture level using a decibel scale and a reference rms texture of 1 μm. This should not be confused with the decibel scale that is used for noise measurement and reporting.

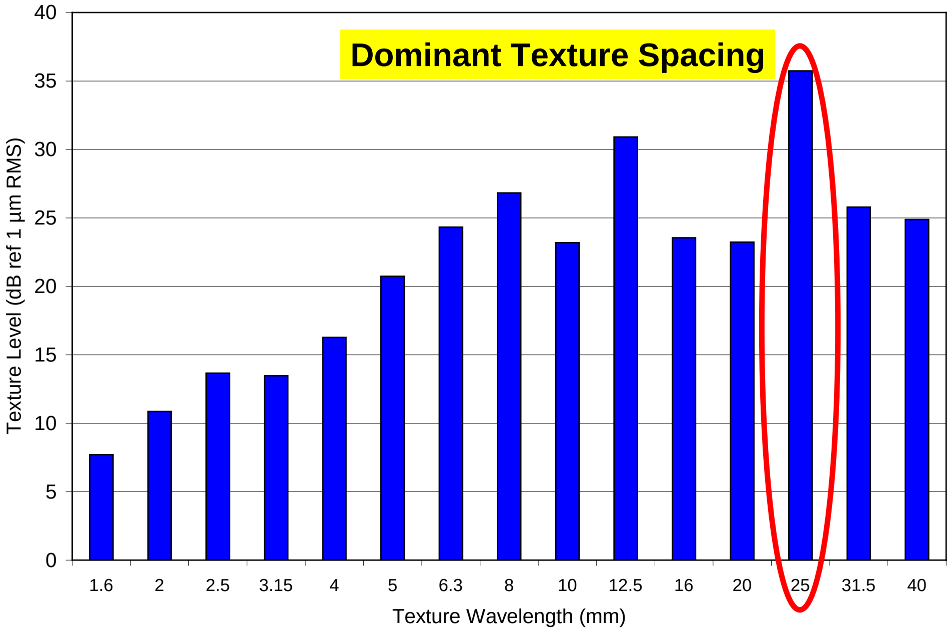

Figure 11. Spectral analysis of texture profile.

Bridging Filter

Ideally, the texture metrics that are calculated should correlate well to the pavement surface characteristics of interest, however this is not always the case. Tire-pavement noise, in particular, is a difficult response to predict given its complexity. One technique that has successfully improved this correlation is the application of a bridging (or envelopment) filter. The filter is applied to texture profiles prior to calculating key texture metrics, most notably spectral analysis.

The specifics of the bridging filter are governed by the response of interest. For example, in the case of tire-pavement noise, the filter geometry is on the same scale as that of the tire tread. As illustrated in Figure 12, the filter simulates how a tire tread would impregnate the texture. The elevation of the filtered profile is calculated as a balance of the downward force on the tire, and the upward reaction due to the elasticity of the tire. This occurs when an equivalent uniform tire rubber displacement (e.g., 1 mm) is achieved (Karamihas 2005). At this point of equilibrium, a single filtered elevation is calculated and stored as the bridged elevation, and the process is repeated again after incrementally moving the filter forward. Mathematically, the filtering process can be further simplified by sorting the texture profile elevations. This is illustrated in Figure 13.

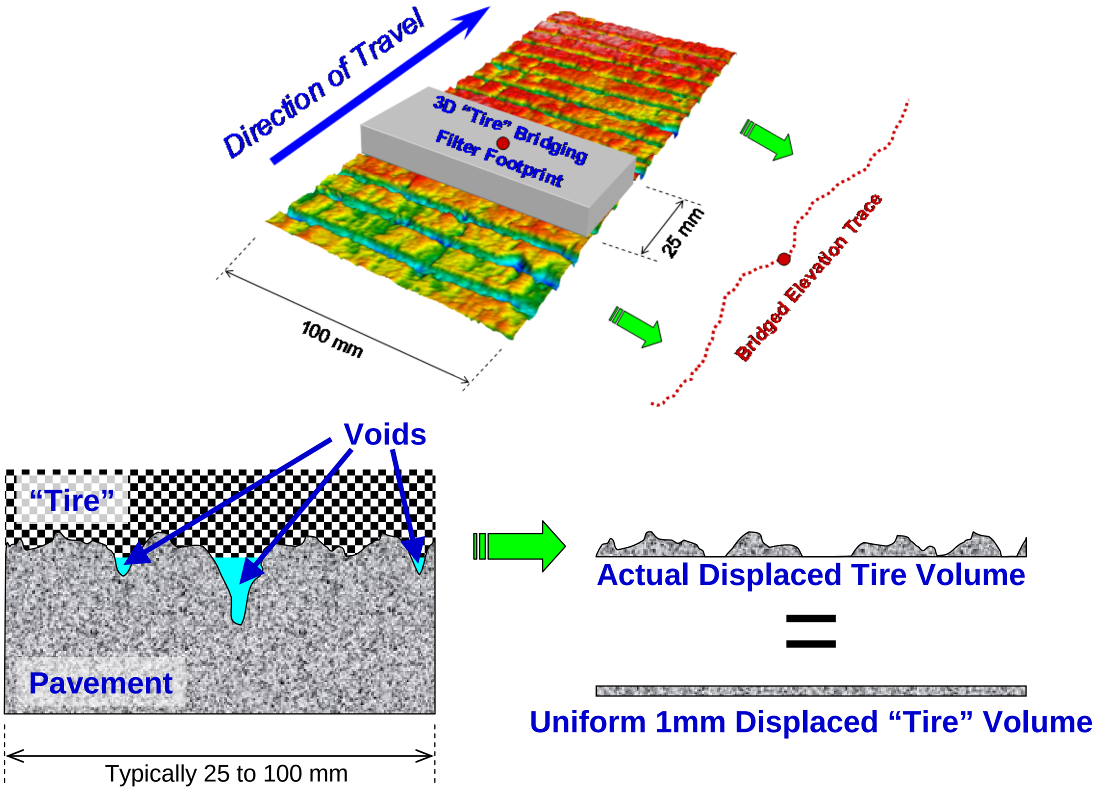

Figure 12. Principles of tire tread bridging filter.

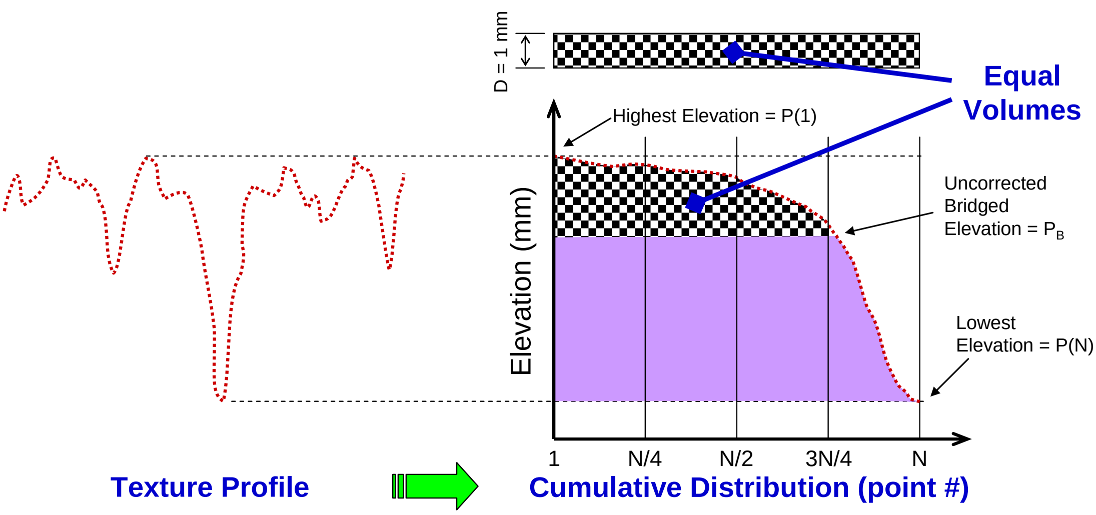

Figure 13. Calculation of bridged elevations using tire tread bridging filter.

Comparing Textures

Figure 14 illustrates 100 mm samples of the two unique textures illustrated in Figure 6: longitudinal tining and diamond grinding.

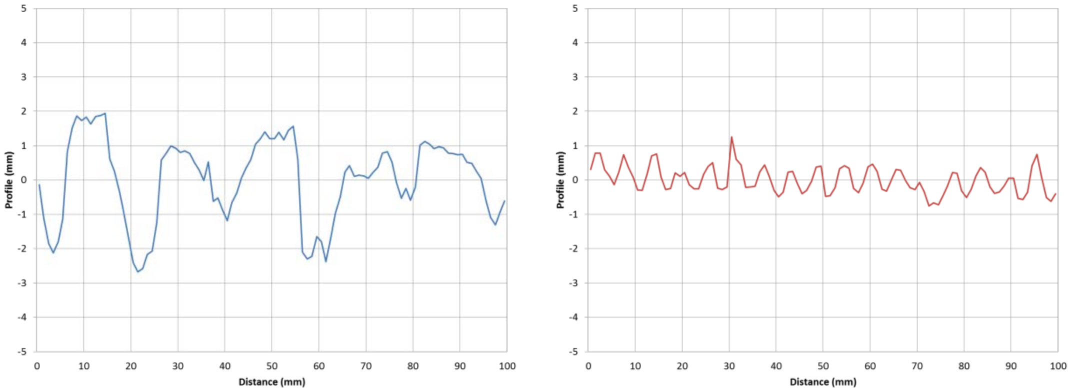

Figure 14. Examples of texture profiles for longitudinal tining (left) and diamond grinding (right).

In order to increase an understanding of the various metrics described herein, a summary of the calculated values for the two profiles in Figure 14 are given in Table 1.

Table 1. Summary of texture metrics calculated for texture profiles in Figure 14.

Texture Metric	**Longitudinal Tining**	**Diamond Grinding**
MPD (mm)	0.89	0.51
R_a (mm)	0.52	0.22
R_q (mm)	0.65	0.26
R_{pk} (mm)	0.31	0.21
R_k (mm)	1.03	0.66
R_{vk} (mm)	1.34	0.19
Skew (*unitless*)	-0.95	0.11
L100 (dB ref 1 μm rms)	41.7	33.5
L50 (dB ref 1 μm rms)	43.2	32.3
L25 (dB ref 1 μm rms)	43.2	33.2
L12.5 (dB ref 1 μm rms)	41.4	32.7
L6.3 (dB ref 1 μm rms)	38.0	31.3
L3.15 (dB ref 1 μm rms)	35.0	30.2

Conclusions

Texture is a vitally important pavement property since it relates to most of what defines functional performance vis-à-vis pavement surface characteristics. It has been shown that measuring the texture of concrete pavements in an accurate and relevant manner requires three-dimensional data, which in the CPSCP was collected using an innovative device called RoboTex.

The data from RoboTex was used to calculate numerous texture metrics including those described herein. The relevance of these metrics to the various surface characteristics depicted in Figure 1 is complex. While some mechanistic models can be formulated, empirical relationships continue to be prolific. For example, MPD can correlate to friction, although the error in this prediction is often significant. Components of tire-pavement noise can be predicted more fundamentally from texture, particularly using the spectral content. However, these predictions are only components of a complicated response, making an accurate prediction of the overall level more difficult.

That said, reasonable models have be identified so that the as-constructed texture can be related to surface characteristics such as tire-pavement noise and friction. With these, better practices have been developed for the design and construction of concrete pavement surfaces.

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