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Evaluation of aggregates surface micro-texture using spectral analysis

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HIGHLIGHTS

- The developed Line Lase Scanner prototype was able to satisfactorily scan the surface profile of aggregates within the first decade of micro-texture.
- The effect of aggregate orientation at the time of scanning is negligible in terms of Power Spectral Density results.
- Texture parameters of **Root Mean Square Roughness and Depth of Surface Smoothness** were consistent with the Power Spectral Density values within the wavelength range of 0.05–0.25 mm.
- The wavelengths within the wavelength range of 0.05–0.25 mm make the greatest contribution to the pavement friction.

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ABSTRACT

Micro-texture of aggregates is a critical component of pavement texture as well as a major contributing factor in roadway safety, especially in low speed conditions. Comprehending the effects of specific wavelengths in micro-texture is essential in the design of pavements to achieve adequate skid resistance. This paper analyzes the micro-texture of aggregates by means of discrete Fourier transform (DFT) and power spectral density (PSD) function. Six aggregates from two different quarries were scanned using a developed line laser scanner (LLS) prototype. The first decade of micro-texture (0.05–0.5 mm) and macro-texture (0.5–2.56 mm) were divided into four and two sub-bands of wavelengths, respectively, in order to better evaluate individual wavelengths. Paired *t*-test was utilized to differentiate the PSD results of the different aggregates. Repeatability of LLS and the effect of aggregates orientation on scanned data were also studied. Filtered micro-texture profiles were obtained from scanned height profiles and subsequently two parameters, root mean square roughness (Rq) and depth of surface smoothness (Rp), were calculated as quantitative measurement of aggregate surface friction for all sub-bands of wavelengths. The results indicated that the wavelengths ranging from 0.05 to 0.25 mm significantly contributes to the aggregate surface frictional properties (Rq and Rp).

1. Introduction

According to the Federal Highway Administration [1], 18,695 fatalities in the United States resulted from roadway departure crashes in 2015. Poor roadway conditions, especially in wet weather conditions, have been identified as a major contributing factor in roadway accidents. A vehicle's loss of traction on wet pavements and the poor visibility due to splash-and-spray are a result of the pavement having inadequate cross-slope and surface texture. Skidding alone in wet conditions contributes to 15–35% of accidents [2]. In low speeds, the rubber friction on wet rough surfaces is about 20–30% smaller compared to that in dry surfaces [3]. Persson et al. stated that the reduced friction contribution of rubber is because of the smoothened pavement surface caused by water that decreases the viscoelastic deformations of rubber in contact with surface asperities [3]. The tire-pavement interaction is what dictates the safety of motorists; pavement design can adjust surface pavement properties to provide safety needed.

The direct force developed in the tire-pavement interface is known as *skid resistance*, a property defined by the properties of the tire, the vehicle speed and the pavement condition and texture. Pavement texture is determinant of the resistance of the pavement surface to a vehicle sliding and skidding [4–6]. The extent of skid resistance on any given pavement is dependent on the design of

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the surface texture—specifically its micro- and macro-texture—as the texture can affect the skid resistance, splash-and-spray, rolling resistance, and tire wear [7]. Pavement surface texture is influenced by many factors, such as aggregate type and size, mixture gradation, and texture orientation, among others.

Pavement texture is the result of the deviations of the surface layer from a true planar surface [8]. The World Road Association, previously the Permanent International Association of Road Congresses (PIARC), has categorized pavement texture by a range of wavelength (λ) and amplitudes (A). The standard specifications, such as the American Society of Testing Materials [8], International Organization for Standardization [9], and German Institute for Standardization (DIN on ISO 13473-1), accepted and incorporated these definitions. The ISO 13473-1 refined the terms incorporating typical amplitudes [10] as follows:

- Micro-texture ($\lambda < 0.5$ mm, $A = 1$–$500\ \mu$m) (where λ is wavelength and A is amplitude).
- Macro- texture (0.5 mm < λ < 50 mm, A = 0.1–20 mm).
- Mega-texture (50 mm < λ < 500 mm, A = 0.1–50 mm).

Micro-texture refers to the small-scale texture of the aggregate surface, which controls the contact between the tire rubber and the pavement surface. Micro-texture is a function of aggregate particle mineralogy, petrology, and source (natural or manufactured), and is affected by the environmental effects and the action of traffic [11,12]. *Macro-texture* refers to the large-scale texture of the pavement surface due to the aggregate particle size and arrangement. In asphalt pavements, the mixture properties (aggregate shape, size, and gradation) which define the type of mixture, control the macro-texture. In concrete pavements, the method of finishing (such as dragging, tinning, grooving or grinding), as well as the width, spacing, and direction of the texturing, controls the macro-texture [13]. Mega-texture has wavelengths in the same order of size as the tire/pavement interface. Examples of mega-texture include ruts, potholes, and major joints and cracks. It affects vibration in the tire walls but not the vehicle suspension, and it is therefore strongly associated with noise and rolling resistance [13–15].

Pavement friction is the result of a complex interplay between two principal frictional force components: adhesion and hysteresis [7,12,13]. Although there are other components of pavement friction, such as tire rubber shear, they are insignificant when compared to the adhesion and hysteresis force components [12]. Thus, friction can be viewed as the sum of the adhesion and hysteresis.

Adhesion is the friction that results from the small-scale bonding/interlocking of the vehicle tire rubber and the pavement surface. It is a function of the interface shear strength and contact area [13,16]. The hysteresis component of the frictional forces results from the energy loss due to enveloping of the tire around the texture. Persson believes that the hysteresis component of the frictional force is developed when the tire slides over the pavement texture asperities. Because of the oscillatory feature of that force, energy dissipation occurs in the rubber that results in heat generation. A length scale λ, which could be very small or very big up to the largest particle of pavement, can be related to an excitation frequency: $f \sim \frac{\mathit{Sliding\ Speed}}{\lambda}$ [3,17–20].

Because the adhesion force is developed at the tire/pavement interface, it is most responsive to the micro-level asperities (micro-texture) of the aggregate particles. In contrast, the hysteresis force developed within the tire is most responsive to the macro-level asperities (macro-texture) formed in the pavement surface. Thus, adhesion governs the overall friction on smooth-textured and dry pavements, while hysteresis is the dominant component on wet and rough-textured pavements [7,13].

As mentioned, micro-texture is an important characteristic of pavement, as it contributes to friction. It is therefore important to carefully select the aggregate properties to exhibit desirable qualities to achieve good performance. The aggregate selection should be based on, but not limited to, the shape, angularity, and texture. To provide enough stability and strength to the asphalt mixture, most specifications limit the amount of aggregate particles with rounded, smooth texture. Aggregates with rough micro-texture provide greater surface area between the tire and the pavement. In the case of wet pavements, a rougher micro-texture contributes to skid resistance by breaking the thin layer of water on the surface, promoting the contact between pavement and tire required to develop the interatomic attractive forces of the adhesion component [21–24].

In 2005, Wang et al. implemented the Fourier morphological analysis method to quantify the surface texture of aggregates on macro-scale to compare quantitative measurements to qualitative human-observation-based judgments. Researchers ranked and quantified 10 different aggregates in terms of shape, angularity, and surface texture. The results showed that the orientation of the aggregate particles in the profile images did not significantly affect the surface texture factors of those particles having similar size; however, the texture factors might be quite different for the aggregates of different sieve size ranges [25]. This was tested by Chen et al. using a 3D laser scanner and adopting a pressure-sensitive film that showed the surface roughness of both micro- and macro-texture of asphalt pavement significantly depends on the proportion of coarse aggregates in the mixture [26,27]. Fourier analysis provides an alternative representation of a waveform in which frequency components of that waveform can be observed and analyzed [28,29]. According to the Fourier theory, all signals, whether real or arbitrary, can be represented as the sum of sinusoidal waves of various amplitudes and frequencies. The Fourier transform (FT) helps to find the amplitudes and the frequencies of these constituent sinusoids [30,31]. Using the FT, the surface roughness power spectrum, or power spectral density (PSD), can be derived from the measured height profile which is the most important parameter of randomly rough surfaces [17,32,33]. Persson et al. concluded that the higher values of PSD reflect more hysteresis contribution to rubber friction. For example, in a wet pavement surface, water smoothens the surface that results in a lower PSD values compared to those of a dry surface [3].

Another study conducted by Slimane et al. in France sought to develop a new method to measure and characterize road surface micro-texture using image analysis. The power spectral density (PSD) of the high-frequency information obtained from surface cartography was studied. The PSD values were normalized and the aggregate surfaces were compared considering the PSD's standard deviation. The researchers then successfully used a combined method of geometric/frequential criterion to find a meaningful relationship between friction values and roughness descriptions [34]. Researchers at the RWTH Aachen University in Germany used Fourier Transformation to convert the surface texture information of the aggregates to spatial frequency domain in order to investigate the wearing behavior of the aggregates. Two-dimensional power spectral density (2D-PSD) was calculated before and after the polishing test to evaluate the surface roughness and the texture changes. Comparing 2D-PSD values indicated that the polishing test affects surface texture only at very short wavelengths (below 62.8 μm) [35].

Cafiso and Taormina used the average of PSD values for an aggregate sample to define a specific PSD characteristic of that sample. The results showed that this average value was reliable and operationally simple. The researchers believed that a graphic comparison between the PSD curves is insufficient to investigate