CURRENT PRACTICE OF PCC PAVEMENT TEXTURING

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CURRENT PRACTICE OF PCC PAVEMENT TEXTURING

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ABSTRACT

The importance of surface texture characteristics to roadway safety was first recognized during the late 1940s and early 1950s when increases in traffic volumes and vehicle speeds resulted in increases in wet weather crashes and fatalities. As a result, agencies conducted extensive research, including experimental projects around the country, to better understand and improve the surface conditions of portland cement concrete (PCC) pavement in wet-weather conditions. As new surface texturing methods were tried and evaluated, pavement engineers recognized that a general trade-off existed between friction and noise; i.e., surface textures with higher friction tended to produce greater tire-pavement noise.

Although considerable information exists on the influence of surface friction characteristics on safety and tire-pavement noise, it is dispersed among numerous sources. The purpose of this paper is to identify and summarize key texture-related information and recommendations based on the current state of the practice. Specifically, this document introduces pavement texture nomenclature; discusses methods of measuring and quantifying texture; describes traditional and innovative texturing methods/techniques; summarizes respective conclusions pertaining to the influence of texture characteristics on surface friction and tire-pavement noise; and provides current state-of-the art texture-related recommendations.

INTRODUCTION

The importance of surface texture characteristics on roadway safety was first recognized during the late 1940s and early 1950s when increases in traffic volumes and vehicle speeds resulted in increases in wet-weather crashes and fatalities (*1*). As a result, agencies began conducting experimental projects to better understand and improve the surface conditions of portland cement concrete (PCC) pavement in wet-weather conditions.

Pavement surface friction (previously referred to as “skid resistance”) is the retarding force developed at the tire-pavement interface that resists sliding when braking forces are applied to the vehicle tires (*2*). While adequate surface friction generally exists on dry pavements, the presence of water reduces the direct contact between the pavement surface and the tire. If this film of water becomes sufficiently thick or if vehicle speeds are sufficiently high, the tires can lose contact with the pavement surface, resulting in a dangerous phenomenon known as hydroplaning (*2*).

Water on the pavement also contributes to splash and spray. This occurs when standing water on the surface is picked up by vehicle tires and splashed or sprayed into the air. Such airborne water can cause a reduction in visibility of the drivers in vehicles traveling next to or closely behind the vehicle. Past research has suggested that 15 to 35 percent of wet weather crashes involve skidding, and 10 percent are caused by poor visibility due to splash and spray (*3*). Based on data such as these, it is important for pavement engineers to select surface texturing that reduces hydroplaning at higher speeds while providing sufficient surface drainage so that splash and spray are minimized (*3*).

As new surface texturing methods were tried and evaluated, pavement engineers recognized the corresponding influence of the texture (type, characteristics, and quality) on tire-pavement noise. Specifically, it was recognized that a general trade-off existed in that surface textures with higher friction also tended to result in greater tire-pavement noise. Since noise is a function of vehicle speeds, it is a particular concern for pavements in urban areas that are designed to carry higher speed traffic. Whereas many surface texturing types are effective at reducing noise-related problems, a pavement engineer must be cognizant of the effects of those textures on pavement friction (*4*).

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PAVEMENT TEXTURE COMPONENTS

It is a pavement's microtexture and macrotexture that have the largest impact on friction, splash and spray, and tire-pavement noise. These texture components are described in detail below.

- Microtexture—The fine-scale roughness contributed by the fine aggregate in the concrete mortar (*5*). Specifically, microtexture is defined by wavelengths of 1 μm to 0.5 mm (0.0004 in to 0.02 in) and vertical amplitudes less than 0.2 mm (0.008 in) (*6*). Good microtexture is usually all that is needed to provide adequate stopping on a PCC pavement in dry-weather conditions, or in wet-weather conditions when speeds are under 80 km/h (50 mph).
- Macrotexture—Texture with wavelengths of 0.5 mm to 51 mm (0.02 to 2 in) and vertical amplitudes between 0.1 mm and 20 mm (0.004 to 0.8 in) (*6*). Macrotexture is most commonly produced through small surface channels, grooves, or indentations that are intentionally formed (plastic concrete) or cut (hardened concrete) to allow water to escape from beneath a vehicle's tires. PCC pavements constructed for speeds 80 km/h (50 mph) or greater require good macrotexture to prevent hydroplaning (*3*). The impact of macrotexture on friction and noise is greatly influenced by the selected surface texture and its detailed channel or groove pattern (width, depth, spacing, and side angle [skew]) (*7*).

MEASUREMENT OF SURFACE TEXTURE

Measuring pavement macrotexture has been a common practice in Europe for many years. Recognition of the importance of the role of pavement macrotexture in providing adequate surface friction has been increasing in the United States (*8*). A recent questionnaire focused on the current practices associated with providing and measuring friction and texture characteristics (*9*). In that survey, only 5 of 42 responding states reported that they measured macrotexture (by various methods) and no states currently specify minimum requirements for macrotexture (*9*).

A number of different methods have been used to measure surface texture. Some of the most commonly used statistics, and the measurement methods used to collect the data needed to compute them, are presented below.

Mean Texture Depth (MTD)

The mean texture depth (MTD) is a texture characteristic that is determined using the traditional *volumetric* method (commonly referred to as the "sand patch test"). The volumetric method involves using a special tool to spread a specified volume of very small glass spheres (similar to the size of sand particles) on the pavement in a circular motion (*10*). The MTD is then computed by dividing the known volume of glass spheres by the calculated average of four equally spaced diameters of the circular patch (*9*).

In order to provide adequate surface friction, the average MTD should be 0.8 mm (0.03 in) with a minimum of 0.5 mm (0.02 in) for any individual test (*3*). A recent survey found that New Zealand, Quebec, and South Australia had stated MTD intervention levels in the 0.4 to 0.9 mm (0.015 to 0.035 in) range on higher speed roadways (*9*). Great Britain has also reported having a goal of providing an MTD of 1.5 mm (0.06 in) on their newly constructed PCC pavements (*9*, *11*).

Mean Profile Depth (MPD)

In the past decade, advances in laser technology and computational power have led to the development of systems that measure pavement longitudinal profile at traffic speeds (*9*). The mean profile depth (MPD) is a statistic computed by analyzing 102-mm (4-in) segments of the collected profile data. After dividing each segment in half, the average of the highest profile peaks in each half is computed (peaks are measured in relation to a determined zero mean profile). The MPD is then computed as the average of all individual segment peak averages (*9*). Recent research has indicated that MPD is the best parameter to describe macrotexture for the prediction of wet pavement friction (*12*, *13*, *14*). The MPD is measured using modern high-speed vehicle-mounted laser-based measuring devices or using new portable devices such as the Circular Texture Meter (CTMeter).

The measured MPD may be used to estimate the more traditional MTD measurement. However, when MPD is used to predict MTD, the result is referred to as an estimated texture depth [ETD]). The ETD is comparable to the MTD value that results from the volumetric method (*9*). The expression given for the ETD in the ISO and ASTM standard practices for calculating MPD is the following (*13*, *14*):

$$\mathrm{ETD} = 0.8 \times \mathrm{MPD} + 0.2 \qquad \text{(Eq. 1)}$$

Note: ETD and MPD are reported in mm.

One specific example of a high-speed laser system used to measure pavement macrotexture is the ROad Surface ANalyzer (ROSAN). The ROSAN system consists of a van equipped with laser sensors mounted on the vehicle's front bumper. The instruments can measure the profile accurately at speeds up to 112 km/h (70 mph) (*9*). The laser measurements are then analyzed and used to compute ETD.

The CTMeter, introduced in 1998, uses a laser to measure the profile of a circle 284 mm (11.2 in) in diameter or 892 mm (35 in) in circumference (*8*). The profile is then divided into 8 segments of 112 mm (4.4 in) and the mean depth of each segment or arc of the circle is computed according to the standard practices of ASTM and ISO (*13*, *14*). It has been found that the MPD is most accurately estimated when all eight segment depths are averaged. Excellent results have been observed using this method (even on grooved pavements) and the MPD produced by the CTMeter is highly correlated with MTD (*9*).

Outflow Time (OFT)

The outflow time (OFT) is a texture-related statistic measured using the Outflow Meter. The Outflow Meter consists of a transparent vertical cylinder that rests on a rubber annulus placed on the pavement. A valve at the bottom of the cylinder is closed and the cylinder is filled with water. The valve is then opened and the time is measured for the water level to fall by a fixed amount. This measured amount of time is the OFT. The OFT is highly correlated with the MTD and the MPD on non-porous pavements (*9*). The correlation between MTD and OFT, as measured by the FHWA outflow meter for nonporous surfaces at the NASA Wallops Flight Facility, was found to be (*9*):

$$\left(\frac{1}{\mathrm{OFT}}\right) = 0.58 \times (\mathrm{MTD}) - 0.15 \qquad R^2 = 0.99 \qquad \text{(Eq. 2)}$$

Note: OFT is reported in seconds and MTD is reported in mm.

International Friction Index (IFI)

The International Friction Index (IFI) was proposed in 1992 by PIARC as a method of incorporating simultaneous measurements of friction and macrotexture into a single index representative of a pavement's frictional characteristics. The IFI is dependent on two parameters that describe the skid resistance of a pavement: a speed constant (S_p) derived from the macrotexture measurement that indicates the speed dependence of the friction, and a friction number (F60) that is a harmonized level of friction for a speed of 60 km/h (36 mph) (*15*, *9*). Equation forms for these IFI parameters are as follows (*9*):

$$S_p = a + b \times TX \qquad \text{(Eq. 3)}$$

$$F60 = A + B \times FRS \times e^{\frac{S-60}{S_p}} + C \times TX \qquad \text{(Eq. 4)}$$

where:

S_p = IFI speed constant.
a,b = Constants determined for a specific macrotexture measuring device.
TX = Macrotexture parameter reported by the specific macrotexture measuring device (e.g., MTD or MPD).
F60 = IFI friction number.
A,B,C = Constants determined for a particular friction measuring device (*15*).
FRS = Measurement of friction by a device operating at a slip speed (S).
S = Slip speed of friction measurement (i.e., the speed at which a locked wheel is dragged for friction measurement).

One advantage of IFI is that tests may be conducted at any speed, since the F60 value for a pavement is the same regardless of the slip speed used (*9*). It is believed that the adoption of the IFI will eliminate concerns related to the use of different equipment/procedures and test speeds when measuring surface friction.

ASTM has developed a standard practice for determining IFI and the Council for European Normalization currently has a draft standard under consideration (*9*, *15*). The preferred macrotexture measurement characteristic for the computation of the speed constant is the MPD, for which ASTM and ISO have developed standards (*9*, *13*, *14*). Modern equipment are now capable of measuring macrotexture at highway speeds. Currently, CTMeter results can be combined with the Dynamic Friction Tester (DFT) results to compute IFI.

TEXTURING OF PLASTIC CONCRETE

Early methods of surface texturing of new PCC pavements primarily consisted of "shallow" texture techniques such as broom finishing or burlap dragging. In 1963, 60 percent of the highway departments used burlap drag, and 12 percent specified either a burlap drag or a broom finish (*16*). By 1969, 46 states were using a burlap drag as their primary texturing technique on new PCC pavements (*7*). Recognizing the need for better friction characteristics, many SHAs continued to experiment with different machines and finishing tools in an effort to produce "deep" macrotexture on fresh concrete (*1*, *7*). Research results from this time period indicated that while these shallow texturing techniques resulted in a very quiet riding surface, they did not provide adequate skid resistance at high speeds.

During the early 1970s, a number of independent SHA studies demonstrated that improved surface friction characteristics were provided by the practice of transverse tining (*17*, *18*, *19*, *20*). Texturing guidelines published by the ACPA in 1975 and by the American Association of State Highway and Transportation Officials (AASHTO) in 1976 reflected these research results as they recognized the friction characteristic improvements of transverse tining or grooving over the traditional practices of burlap dragging or brooming (especially on high speed pavements) (*21*, *22*). By the end of the 1970s more than 33 states were using, or planned on using, transverse tining as their texturing technique on fresh PCC (*18*). Transverse tining continues to be the most common texturing technique used by SHAs today. Brief descriptions of commonly used texture methods are presented in table 1. The remainder of this section discusses details associated with different plastic concrete texturing techniques.

Burlap Dragging, Transverse and Longitudinal Brooming, and Artificial Turf Dragging

For over 20 years the general consensus (based on research and past experience) has been that shallow texturing by itself will not provide a safe, durable surface on high-speed facilities. However, some recent experiences contradict this viewpoint. As a result of a recent evaluation of surface texture practices in Minnesota, in 1999 the Minnesota DOT returned to the use of a longitudinal artificial turf drag texture as the sole texturing technique on all new PCC pavements (*5*). Collected friction and noise data indicate that the artificial turf drag texture provides surface friction and noise qualities equivalent to that provided by asphalt pavements. Minnesota's current artificial turf drag specification requires a mean texture depth of 1.0 mm (0.04 in) or more (based on the average of 4 sand patch tests per day) and has a goal of creating the following friction numbers: FN40S of about 32 and a FN40R of about 45 (*5*). Data presented in previous studies had shown that these dragging techniques typically produced texture depths in the range of 0.2 to 0.3 mm (0.008 to 0.012 in) (*4*, *23*).

Transverse Tining

Transverse tining, preceded by a longitudinal artificial carpet or burlap drag, is currently the most commonly used surface texture method on new higher-speed (80 km/h or greater) PCC pavements. This texture combination has gained popularity as a cost-effective method of consistently providing a durable, high-friction surface. Transverse tining improves a pavement's friction characteristics as the transverse grooves are very effective at quickly removing surface water from the driving lanes and onto the shoulder (even on flat longitudinal grades) (*3*). While experience has shown that transverse tining is extremely effective at providing high quality friction characteristics over the life of the pavement (up to 30 years), it has also been associated with an objectionable tonal quality (a whine) resulting from the tire-pavement interaction. However, this whine can be greatly reduced with the choosing of proper tine spacing, depth, and skew.

Longitudinal Tining

While not as popular as transverse tining, longitudinal tining has been used in a small number of states including California, Virginia, Michigan, Iowa, and Colorado (*3*). Although longitudinally tined surfaces are generally quieter than transversely tined surfaces, data has shown that they consistently exhibit poorer surface friction characteristics than their transverse counterpart due to the increased time needed to drain the surface. This increase in drain time therefore results in an increased probability of hydroplaning and splash and spray problems. One frictional advantage of longitudinal tining over transverse tining is, however, realized on horizontal curve sections. With the longitudinal grooves, vehicles on horizontal curves have a greater tracking force acting to prevent them from skidding off the curve. Wider longitudinal grooves should be avoided as they have been found to be bothersome to motorcyclists and drivers of vehicles with smaller tires due to the feeling that steering control has been taken by the pavement.

Innovative Texture Techniques

A number of experimental texturing techniques have been tried in both Europe and the United States. This section briefly describes the usage and effectiveness of some of these innovative techniques.

Exposed Aggregate Texturing

An exposed aggregate texturing is the process of removing the surface mortar of the concrete in order to expose hard and polish-resistant aggregates (*24*). Aggregate exposure is commonly accomplished by two different techniques: 1) watering and brushing the fresh concrete surface with a rotary brush; 2) spraying the surface with a set retarder immediately after placement, followed by a mechanical brushing 24 hours later to remove the mortar that has not set (*25*). The average texture depth is targeted to be 0.9 mm (0.035 in) as measured by the sand patch test (*3*).

Though widely used in European countries, the exposed aggregate technique has not been widely used in the United States. Overall, when properly designed and constructed, the European experience has found that exposed aggregate surfaces have performed very well. Specific favorable characteristics include low noise (similar to porous asphalt), excellent high-speed skidding resistance (equivalent to transversely tined pavements), good surface durability, and low splash and spray. Disadvantages of this method include 1) high-quality aggregates are required throughout the thickness of the wearing course, and 2) although construction of the surface is not difficult, contractors often experience a learning curve as they gain familiarity with the practice.

Chip Sprinkling

Originating in Belgium in the early 1970s, chip sprinkling is the practice of strewing polish-resistant stones of a specified size (e.g., 14 to 20 mm [0.6 to 0.8 in]) evenly onto the surface of the already compacted and profiled fresh concrete and setting them in such a way that they slightly protrude from the surface, thus creating macrotexture (*26*). Although this practice can result in an extremely noisy surface, the use of high quality chippings (aggregates) can help reduce the associated noise while providing satisfactory surface friction (*7*).

Longitudinal Plastic Brushing

Longitudinal plastic brushing consists of a longitudinal burlap drag followed by a plastic brush. Successful results from Spain have showed this technique to be effective at providing high-friction characteristics while minimizing tire-pavement noise (*3*). Specifications for this texturing technique include a minimum of 30 percent siliceous sand (to ensure satisfactory microtexture) and a required average texture depth of 0.7 to 1.0 mm (0.03 to 0.04 in) (*3*). While published reports of the use of this technique have indicated friction characteristics similar to porous asphalt, wet weather accident rates for this texture compared to other textures or surface types is not currently available (*3*).

Porous Concrete

The principle of this technique is to create voids in the concrete (e.g., 20 percent by volume of concrete) so that water can quickly drain from the surface (*7*). The initial experience in Belgium with this surface type showed poor durability in freezing weather; however, the durability of these mixtures has since been improved with the addition of polymers and the use of a higher cement content (*3*, *27*, *28*). If well maintained, this surface type has provided surface texture characteristics similar to those associated with an open-graded HMA pavement (*3*). As with porous HMA surfaces, the surface must be routinely cleaned to prevent small particles from clogging up the pores that give the surface its beneficial drainage capabilities.

TEXTURING OF HARDENED CONCRETE

The process of using texturing techniques to improve surface friction and reduce tire-pavement noise has not just been limited to new construction (plastic concrete). During the early 1950s, a California road engineer introduced a machine designed to bring the PCC surface into tolerance by grinding localized high spots or “bumps” (*29*). This machine, termed the “Bump Cutter,” accomplished this task by using a rotating drum that was made up of a large number of diamond saw blades placed closely together on a single shaft. The first documented use of the Bump

Cutter was on a new runway on a military base in Arizona in 1956 (*29*). The first usage of a Bump Cutter machine on an existing PCC highway occurred in 1965 on the San Bernardino Freeway east of Los Angeles, California (*29*). As a result of this initial successful project, diamond grinding became a widely accepted method of concrete surface restoration during the 1970s. Today, diamond grinding is just one of a number of texturing techniques currently available for restoring surface friction or lowering tire-pavement noise on existing PCC pavements. Table 1 contains brief descriptions of texture methods commonly used on hardened concrete. More details of these methods are presented below.

Diamond Grinding

Although most commonly used to remove surface irregularities and roughness (e.g., transverse joint faulting), diamond grinding has been found to be effective at improving surface friction and decreasing tire-pavement noise. Diamond grinding positively impacts a pavement’s frictional characteristics by restoring surface microtexture and providing some macrotexture. The resultant texture leads to improved surface drainage, which reduces the potential for hydroplaning and subsequent wet-weather accidents. Many different studies have documented this immediate improvement in frictional characteristics (*30*, *31*).

Diamond grinding has also been found to be an effective method of reducing tire-pavement noise. In a recent pavement noise study by Kuemmel et al., diamond grinding of recently constructed, transverse tined PCC pavements was found to reduce exterior noise levels 2 to 3 dB (*23*). In addition, the diamond ground PCC pavement in this study did not exhibit any discrete frequencies (spikes) in the interior or exterior noise spectrum that cause the objectionable whine described by pavement users and passers-by (*23*).

Diamond Grooving

Diamond grooving is the process of cutting grooves into a hardened PCC surface using diamond saw blades. These grooves are primarily cut in the longitudinal direction at a center-to-center spacing of 19 mm (0.75 in); in some cases, (such as intersections) transverse grooving may be conducted. The principal objective of diamond grooving is to provide deep channels in the surface that provide an escape route for surface water, thereby reducing hydroplaning and wet weather crashes. Longitudinal grooving is also beneficial in providing increased lateral control for vehicles, especially on transitions and superelevated curve sections (*5*).

Diamond grooving was developed in California during the late 1950s by the inventor of the Bump Cutter machine. By 1970, nearly 320 km (200 mi) of pavement had been grooved in California (*29*). Since then, diamond grooving has been the traditional means of improving friction characteristics on airports, bridges, and in high-accident locations on highways.

Abrading (Shotblasting)

Similar to sandblasting, abrading (shotblasting) uses equipment to hurl small abrasive media at the pavement surface (within an enclosed housing) in order to remove a thin layer of mortar and aggregate (0 to 6 mm [0 to 0.25 in]). Although primarily used to prepare and clean a PCC surface for bonded PCC overlays, the abrading process leaves exposed sand-sized particles that provide good microtexture with beneficial friction characteristics.

IMPACT OF TEXTURE ON SURFACE FRICTION

The importance of maintaining adequate pavement surface friction is evident as pavement safety continues to be a major concern to most highway agencies around the world. A 1980 report by the National Transportation Safety Board (NTSB) estimated that 16 to 18 percent of the fatal accidents in the United States occurred on wet pavements (*32*). Similarly, the Nationwide Personal Transportation Survey conducted in 1990 reported that of almost 25 million reported accidents, about 19 percent occurred when the pavement was wet (*33*). Because of this continued concern, routinely assessing surface friction should be an integral component in the process of monitoring pavement functional performance.

Today, the majority of agencies in the United States measure pavement friction with an ASTM locked-wheel trailer using either a standard ribbed or smooth (blank) tire (in accordance with ASTM E 274 or ASTM E 524, respectively) to determine *friction numbers* (*9*, *34*, *35*). The friction number (formerly referred to as *skid number*) is computed as 100 times the force required to slide the locked test tire (at the stated speed, usually 64 km/h [40 mph]) divided by the effective wheel load (*23*). Friction numbers are reported in the form of: FN(Test Speed [in mph]) followed by an R if a ribbed tire was used or an S if a smooth-tread tire was used. If the test speed is expressed in km/h it is enclosed in parentheses. For example, if a ribbed tire was used in a locked-wheel trailer test at a test speed of 64 km/h (40 mph), the friction number would be reported as FN(64)R or FN40R (metric and English units, respectively). As a general rule of thumb, FN40R values in the 30 to 40 range are targeted for major highways (interstate highways and other roads with design speeds more than 65 km/h [40 mph]). Lower friction numbers are generally acceptable for low-speed and low-volume pavements (less than 3,000 average daily traffic).

The following list summarizes many of the observed impacts of surface texture on a pavement's friction characteristics:

- Both microtexture and macrotexture influence tire-pavement friction. Effective microtexture typically provides adequate surface friction on dry pavements at all speeds and on wet pavements at slower speeds, whereas macrotexture is typically required to provide adequate friction in wet conditions at higher speeds.
- Shallow drag-type textures by themselves may not produce surface textures with either adequate or long-lasting surface friction. Deeper grooving techniques are more effective at providing better surface drainage and higher friction characteristics (thereby reducing wet-weather crashes).
- Transversely grooved textures generally provide higher surface friction, and less splash and spray potential, than longitudinal grooves. However, longitudinal grooves provide better directional control and resistance to lateral movement, have less tire noise than their transverse counterpart, and are easier to achieve than transverse tining.
- Transverse tining on a PCC pavement with high-quality materials can provide high-friction properties and low long-term noise characteristics equivalent to those exhibited by dense-graded asphalt. Splash and spray on transversely tined sections has also been found to be less than that on dense graded HMA (*3*).
- Although grooving or tining is often effective at improving the skid resistance on a PCC pavement, the grooves typically cause the resulting surface to be more susceptible to wear, particularly where chains and studded tires are in use.
- The quality of the construction and curing practices are also important factors that influence the durability and overall effectiveness of the provided surface texture.
- Well designed and constructed longitudinally tined PCC pavements can have adequate durability and friction numbers when compared to either transversely tined PCC pavements or dense-graded HMA pavements (*3*).

The results of a recent study by Kuemmel et al. show an example of comparative friction numbers of different surface textures (*23*). In this study, friction measurements were taken on 46 pavement sections in 9 different general categories. Measurements were taken at 64 km/h (40 mph) with a smooth tire (FN40S) in accordance with ASTM E 524 (*35*). A bar chart summarizing the average observed friction numbers for each general category is presented in figure 1.

IMPACT OF TEXTURE ON TIRE-PAVEMENT NOISE

Recent research has found that *objectionable* interior noise is more associated with tonal quality (specific frequencies) rather than total noise level (*23*). This objectionable tonal quality (often described by users as a *tire whine*) is primarily the result of spikes in sound pressures at different frequencies. An example of such spikes is shown in figure 2 in which spectra for two different surfaces from a recent Wisconsin study are presented (*36*). Two important discoveries from the recent research include 1) different texturing techniques produce different tonal qualities (noise spectra), and 2) tonal quality can differ without changes in the total overall noise level. Therefore, eliminating peaks such as those shown in figure 2 has been found to be the key to reducing a pavement's tire whine or perceived loudness (*5*).

Specific recent texture/noise-related findings are summarized as the following:

- Tine or groove depth, width, spacing, and orientation are all major factors affecting tire-pavement noise (*7*).
    - Transverse tinings with uniformly spaced tines 13 mm (0.5 in) or greater have been found to produce an objectionable tonal quality (pressure spikes at specific frequencies) that users interpret as a *tire whine*.
    - Randomly varying the transverse tine spacing can reduce the tonal quality problems, however, this desired variability can be difficult to achieve. Some experience has shown that patterns intended to be random were actually fairly uniform (*23*).

  - Transverse tining, properly constructed on a PCC pavement with high-quality materials, can provide low long-term noise characteristics similar to dense-graded HMA (*3*).
  - Tire-noise increases with tine width. Research shows mixed data regarding the impact of tine depth on tire-noise (*3*).
  - The skewing of transverse tining (i.e., tining that is not perpendicular to the direction of traffic) has been found to reduce tire-pavement interaction noise.
  - Longitudinal tining, shallow texture drags, diamond grinding, and abrading do not exhibit the same prominent objectionable tonal spikes observed with uniform transverse tining (*5*).
  - The use of burlap or other types of drags preceding the transverse tining seems to reduce tire-pavement noise (*7*).
- Noise generated by PCC pavement decreases with time (aging), while HMA pavement noise increases (*7*).
- Diamond grinding, if deep enough to remove most of the uniform transverse texture, can be an effective restorative treatment for PCC pavements with excessive whine.

In the recent study by Kuemmel et al. (*23*), user perceptions of loudness were ranked for 20 surface textures (some duplicates). These subjective rankings, along with the actual measured interior and exterior noise levels, are presented in table 2 (*37*).

SUMMARY AND RECOMMENDATIONS

This paper is the result of a recent literature review conducted to summarize the state of practice for PCC surface texturing. Specifically, in addition to introducing common texture-related definitions, the paper focuses on compiling current information related to the following:

- Methods of measuring surface texture.
- Common characteristics used to quantify surface texture.
- Common texturing techniques used on both plastic and hardened PCC surfaces.
- Impact of texture on surface friction and tire-pavement interaction noise.

Overall, the review of recent literature emphasizes that when selecting a particular surface texturing type and its specific characteristics (texture depth, width, spacing, and orientation) it is important for the pavement engineer to remain focused on selecting a final surface texture that 1) provides adequate surface friction to minimize wet-weather crashes, and 2) minimizes of tire-pavement interaction noise. To accomplish this task, the following general texturing techniques are recommended depending on the posted roadway speed:

- **Lower Speed Roads** (≤ 72 km/h [45 mph]). For lower speed roadways, a traditional burlap drag, turf drag, or brooming texture (i.e., no tining) can be sufficient for safety, and is less costly and quieter than most tine textures on a roadway (*5*). However, agencies should specify a minimum macrotexture (MTD's are typically specified MTD in the range of 0.8 to 1.5 mm [0.03 to 0.06 in]) and verify its provision with testing (e.g., with sand patch tests).
- **Higher Speed Roads** (> 72 km/h [45 mph]). For higher speed roadways, a traditional burlap or turf drag, combined with random transverse or longitudinal tining (based on the specific project conditions) is recommended.

When transverse or longitudinal tining is selected as a texturing method, the best performance has been exhibited when the specific characteristics presented in table 3 are utilized.

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TABLE 1 Descriptions of Texturing Methods Commonly Used on Plastic and Hardened PCC Pavements (*5*, *37*)

Texture for Fresh Concrete	Description
Burlap Dragging	Produced by trailing moistened coarse burlap from a device that allows control of the time and rate of texturing – usually a construction bridge that spans the pavement. Produces 1.5- to 3.0-mm (0.063 to 0.125-in) deep striations.
Artificial Turf Dragging	Produced by trailing an inverted section of artificial turf from a device that allows the control of the time and rate of texturing – usually a construction bridge that spans the pavement. Produces 1.5- to 3.0-mm (0.063 to 0.125-in) deep striations when using turf with 77,500 blades/m^2 (7,200 blades/ft^2).
Transverse Brooming	Obtained using either a hand broom or mechanical broom device that lightly drags the stiff bristles across the surface. Produces 1.5- to 3.0-mm (0.063 to 0.125-in) deep striations.
Longitudinal Brooming	Achieved in similar manner as transverse broom, except that broom is pulled in a line parallel to the pavement centerline.
Random Transverse Tining (Perpendicular or skewed)	Achieved by a mechanical device equipped with a tining head (metal rake) that moves across the width of the paving surface-laterally or on a skew. (A hand tool is sufficient on smaller areas.) Optimal dimensions are: 10- to 57-mm (0.375- to 2.25-in) random center-to-center tine spacing, 3- to 6-mm (0.125- to 0.25-in) tine depth, and 3-mm (0.125-in) tine width. Often used in conjunction with a burlap drag or artificial turf drag.
Longitudinal Tining	Achieved in a similar manner as transverse tining, except that tines are pulled in a line parallel to the pavement centerline. Optimal dimensions are: 19-mm (0.75-in) uniform tine spacing, 3- to 6-mm (0.125- to 0.25-in) tine depth, and 3-mm (0.125-in) tine width.
Innovative Texturing Techniques	A number of textures, construction methods, and innovative PCC surface types have been investigated in both foreign countries and the United States. Examples of these include texturing techniques such as exposed aggregate texturing, chip sprinkling, longitudinal plastic brushing, and experimentation with a porous PCC surface. Foreign usage and research has shown good experiences with many of these techniques/methods; however, they are all still considered experimental in the United States.
Texture for Hardened Concrete	**Description**
Diamond Grinding	Longitudinal, corduroy-like surface created with equipment using diamond saw blades gang-mounted on a cutting head. The cutting head produces 164 to 197 grooves/meter (50 to 60 grooves/foot) and can remove 3 to 19 mm (0.125 to 0.75 in) from the pavement surface.
Diamond Grooving	Grooves sawed longitudinally into the highway surface. Made by same equipment used for diamond grinding. Typically, the grooves are 6 mm (0.25 in) deep, 3 mm (0.125 in) wide, and spaced 19 mm (0.75 in) apart.
Abrading (Shotblasting)	Etched surface produced by equipment that hurls abrasive media within an enclosed housing. The abrasive media impacts the surface and removes a thin layer of mortar and aggregate. The depth of the removal is controllable and the dust is vacuumed into a baghouse.

TABLE 2 User Perception and Actual Noise Levels Associated With Different Surface Textures (*23*)

Subjective Rank	Texture	Interior dBA	Exterior dBA
1	19-mm (0.75-in) random transverse tine with 1:6 skew	67.6	82.4
2	19-mm (0.75-in) random transverse tine with 1:4 skew	67.2	83.1
3	Asphalt – SHRP	65.9	81.1
4	Variable transverse tine	67.7	81.0
5	25-mm (1-in) uniform longitudinal tine	68.0	83.9
6	Exposed aggregate	67.4	NA
7	38-mm (1.5-in) random transverse tine	66.9	82.6
8	13-mm (0.5-in) uniform transverse grooving	69.2	83.3
9	19-mm (0.75-in) uniform transverse tine with 3-5 mm (0.13 to 0.2 in) variable depth	70.0	83.8
10	Milled PCC	72.1	84.6
11	13-mm (0.75-in) uniform transverse tine with 3-5 mm (0.13 to 0.2 in) variable depth	68.2	82.8
12	Diamond ground PCC	69.3	81.2
13	25-mm (1-in) random transverse tine	68.8	86.6
14	25-mm (1-in) uniform transverse tine	69.7	86.4
15	25-mm (1-in) random transverse tine	68.6	83.4
16	13-mm (0.75-in) uniform transverse tine	69.3	82.1
17	38-mm (1.5-in) random transverse tine	69.4	87.3
18	19-mm (0.75-in) uniform transverse tine	69.1	84.0
19	Variable transverse grooving	68.6	84.1
20	25-mm (1-in) uniform transverse tine	69.6	86.3

NA = not available

TABLE 3 Recommended texture characteristics for transverse and longitudinal tining (*3*, *23*, *24*, *37*)

Transverse Tining Recommendations	
Tine spacing	Repeated random tine spacing of 10 to 76 mm (0.4 to 3 in) (center-to-center of tines). Recommended when texturing conditions can be optimized (i.e., use of a specially constructed separate machine to provide more control over texturing timing, tine length and spacing, and pressure on the tines). A 3-m (10-ft) long rake with these spacings, was designed using spectral analysis and has been successfully tested by three states. OR Repeated random tine spacing of 10 to 57 mm (0.375 to 2.25 in) (center-to-center of tines) (*37*). *Recommended when less than optimal finishing conditions are present (e.g., less control over the tining procedure or hot and windy conditions). In poorer conditions, this spacing pattern improves the chances of achieving the desired 0.8 mm (0.03 in) target average texture depth.*
Tine depth	3 to 5 mm (0.125 to 0.25 in)
Tine width	3 mm (0.125 in)
Tine orientation	1:6 skew, offset opposite of any skewing of the transverse joints. *(Such skewing has been found to achieve the texture and friction of a conventional transversely tined pavement while also obtaining most of the noise reductions associated with longitudinal tining) (23, 24). Note: if texture considerations are paramount, and a skewed pattern is impractical, randomly spaced transverse tining may be employed; however, this should be carefully designed and built using a highly variable spacing (23).*
Longitudinal Tining Recommendations	
Tine spacing	Uniform tine spacing of 19 mm (0.75 in). *This spacing has been found to provide adequate friction minimize effects on small tired vehicles (24).* It is also recommended that the surface first be subjected to a burlap or artificial turf drag prior to tining.
Tine depth	3 to 6 mm (0.125 to 0.25 in)
Tine width	3 mm (0.125 in)
Mix design	25 percent siliceous sand and highly durable coarse aggregate are recommended to assure both good friction properties and low-noise characteristics (*3*).

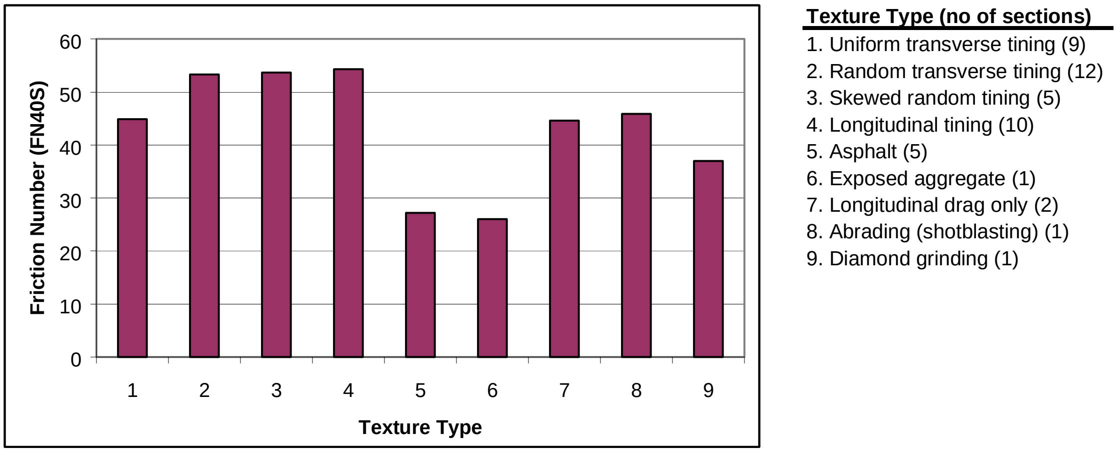

FIGURE 1 Surface friction measured on different surface textures (*23*).

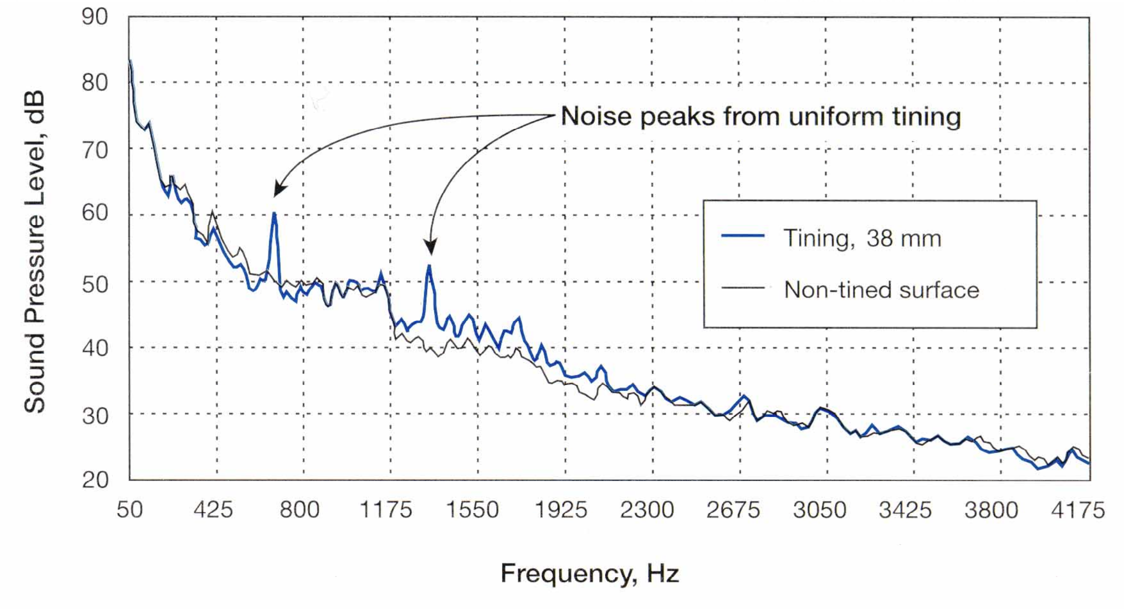

FIGURE 2 Graph from Wisconsin noise study showing the prominent peaks that produce objectionable tire whine (*36*).