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Noise Issues of Concrete-Pavement Texturing

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The second phase of a project researching the texture and noise characteristics of portland cement concrete (PCC) pavements was sponsored by the Wisconsin Department of Transportation and FHWA. The team of Marquette University and HNTB Corporation measured and analyzed the noise and texture parameters of 57 test sites in Colorado, Iowa, Michigan, Minnesota, North Dakota, and Wisconsin. Conclusions pertaining to tire-and-pavement noise were drawn using data from several types of acoustical tests, including objective noise measurements (exterior and interior), subjective noise evaluations, and a prominent frequency analysis. Texture parameters of all test sites were measured with the road surface analyzer (ROSAN). ROSAN texture measurements proved invaluable in analyzing why different textures exhibited different noise characteristics. Both uniform and random transverse tining provide higher interior and exterior noise levels than skewed or longitudinal tining. Transverse tining, even in some random-spaced textures, can cause a discrete frequency or whine. As the depth and width of tining increased, so did the noise levels. Randomly spaced patterns are sensitive to spacing. Ground PCC pavement exhibited no discrete frequencies. Recommendations include the need for better quality control over tining and a wet-pavement-accident study of longitudinal tining. If noise considerations are paramount, longitudinal tining is recommended. If texture is paramount, skewed tining is recommended. If a skew is not possible, then carefully constructed random transverse is recommended.

As traffic volume and speed increased on the nation's highway system, Wisconsin and other states began experiencing noise problems on portland cement concrete (PCC) pavements. It was recognized that the transverse tining on PCC pavements plays a critical role in highway noise.

In 1994, Wisconsin built 16 experimental textures on PCC pavements with the cooperation of the Wisconsin Concrete Pavement Association. Marquette University was hired to analyze noise (both interior and exterior), texture, and friction characteristics of these 16 test pavements. The Center for Highway and Traffic Engineering at Marquette University teamed with the HNTB Corporation to measure and document the source of the noticeable, high-pitch whine associated with uniformly spaced, transverse tining. Because traditional sound-measuring techniques with subjective ranking of sound were inadequate, a new application of the Fast Fourier Transform (FFT) method was used in measurement and analysis of interior noise. The findings (*1, 2*) confirmed subjective perceptions and led to an interim FHWA guideline (*3*) for randomly spaced, transverse-tined PCC pavements. This work was conducted with the cooperation of the Minnesota DOT.

During this time, a number of other states, including Colorado, Iowa, Michigan, Minnesota, and North Dakota, began building experimental pavements as well. In 1997, FHWA launched its High-Performance Rigid Pavement initiative and agreed to fund construction of more experimental textures in Wisconsin. Subsequently, Marquette University and HNTB again documented noise, texture, and friction characteristics of 57 different textures in the six states. FHWA wanted a single research team to measure noise characteristics and to evaluate a uniform texture-measuring procedure in the states, as well. The objective of the study was to develop national guidelines for texturing PCC pavements based on national experience. These guidelines would combine the quietest possible PCC pavement texturing with superior friction and low-noise characteristics.

A detailed literature search is contained in the project report (*4*), which is available from the Wisconsin Department of Transportation (WisDOT).

RESEARCH METHODOLOGY

Exterior Noise Measurements

Noise-Measurement Procedures

Similar to the Phase I study, the exterior-noise-measurement procedure was based on the French–German controlled pass-by method, by which the noise from a single car is measured with the engine running (*5*). Such measurements were performed with a test vehicle under real traffic conditions. A 1996 Ford Taurus was used for all exterior and interior noise measurements. The advantages of this method for the comparison of various road surfaces are described in the Phase I Report (*1, 2*).

Exterior noise levels were recorded with two microphones mounted 1.5 m (5 ft) above the pavement and positioned 7.6 m (25 ft) from the centerline of the nearest traffic lane, 61 m (200 ft) apart from each other. A two-microphone setup was used to monitor potentially significant differences between the microphones due to possible changes in factors such as vehicle speed, driving behavior, road and terrain conditions, and uncontrolled measurement errors.

A Type 2900 Larson–Davis two-channel real-time acoustical analyzer was used for the noise measurements. To achieve a higher frequency resolution, the analyzer's Fast Fourier Transform (FFT) analysis option was used to better examine the frequency spectra associated with the pavements.

The analyzer first was set to analyze noise spectra from 0 Hz to 10 kHz, providing a maximum frequency resolution of 25 Hz for the

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two-channel configuration. Such analyses were carried out for all of the pavements to determine any particular pavement that would exhibit a prominent discrete tone. Thus, 400-line FFT sound pressure levels (SPLs) were recorded for each vehicle pass-by for 10 s in 0.1-s intervals. This duration was based on the time necessary for the vehicle to pass both microphones.

All noise measurements were performed at operating speeds of 96, 104, and 112 km/h (60, 65, and 70 mph) in the right lane. A minimum of three valid runs was needed to collect enough data for each speed. All measurements were performed on dry pavements, with wind velocity less than 24 km/h (15 mph). Quality control of the measured data included review of the field notes and validation that the "pass-by peaks" exceeded the background noise levels by at least 10 dB(A).

Data Summary and Processing

The noise field data were transformed into a spreadsheet format for each of the test runs to identify the noise spectrum associated with the maximum noise levels during vehicle pass-bys. This procedure, performed separately for each analyzer's channel, consisted of identifying the maximum overall sound pressure level (A-weighted) and the values immediately preceding and following the maximum. These three values, along with associated (three) sets of 400-line FFT frequency spectra, were logarithmically averaged to obtain a representative pass-by spectrum for each channel. Finally, all of the test runs' data, both the A-weighted and the frequency spectrum values, were averaged. The resulting data sets were considered representative of the particular pavement, at a certain vehicle speed. Individual noise levels for each vehicle speed and test section were graphed to allow comparisons.

Interior Noise Measurements

The measurement procedure was designed to collect interior noise data for different pavements during continuous (uninterrupted) driving with the same test car (1996 Ford Taurus) that was used for the exterior measurements. For a 5-s duration, the instrument would collect a pre-programmed set of noise data and store them in memory with a specific file name. The duration of tests was based on the time it took for the vehicle to pass through a specific length of the section being tested for both the speeds, to ensure enough time for the instrument to save a newly collected data file and reset itself for the next measurement. The measurement procedure was based in part on the SAE J1477 Recommended Practice for Measurement of Interior Sound Levels of Light Vehicles.

A Type 2900 Larson–Davis two-channel real-time acoustical analyzer was used for the interior noise measurements. The analyzer's FFT analysis was used to determine the narrow-band frequency spectra associated with the pavements.

To collect a full frequency range data, the analyzer first was set to analyze from 20 Hz to 10 kHz, providing a frequency resolution of 12.5 Hz. Such analyses were carried out for all of the pavements to determine a narrower frequency range in which any particular pavement would exhibit a prominent discrete tone. These measurements were taken for two speeds only: 96 and 112 km/h (60 and 70 mph). Three runs per speed were used. Then, to achieve higher frequency resolution of approximately 3 Hz, the narrower range of 250 to 2750 Hz was used. Such measurements were taken at the same three speeds (three runs per speed) as they were for exterior measurements.

The 800-line FFT sound pressure levels were recorded for 5 s for each vehicle pass-by in 1-s intervals. Along with the five linear spectra thus recorded for each pavement, the equivalent 5-s sound pressure level for each individual frequency was calculated for the entire 5-s period.

In addition to the sound pressure measurements, simultaneous audio recordings were taken inside the car. A Sony Type 932 digital data recorder and a microphone were used.

Texture Measurement Using ROSAN

FHWA developed the road surface analyzer (ROSAN), a van equipped with instruments used specifically to measure pavement-texture parameters. ROSAN incorporates a laser sensor mounted on the vehicle's front bumper and can be operated at speeds of up to 112 km/h (70 mph), eliminating the need for costly traffic control to measure texture using the ASTM E965 or Sand Patch method. The laser sensor was set to collect data at 1-mm intervals for approximately 121 m (400 ft), (the distance from 30 m before the first microphone to 30 m beyond the second microphone).

The $ROSAN_v$ (vehicle-mounted) software calculates the mean profile depth (MPD) every meter and an average for the entire 121 m. The estimated texture depth (ETD), a value comparable to the sand patch texture value, is calculated from the MPD by an equation developed specifically for ROSAN. The software also gives an ASTM MPD and ETD, as well. Three runs were made in each wheel path.

The ROSAN software was modified to allow the extraction of texture measurements into a digital format. A program was created to display the extracted data at various sections; to calculate the depth, width, and spacing of each tine; and to estimate the statistics of the tine spacing and dimensions.

$ROSAN_b$ (beam-mounted), which was developed for longitudinally tined pavements, has the laser mounted on a metal beam. The beam is positioned transversely across the right wheel path. A computer-controlled trolley carries the laser across the stationary beam. Readings were taken at multiple locations on each side of the microphone locations and were averaged for the value of ETD. The ETD then was converted to MPD to compare with other MPDs on transverse sections. Details of the ROSAN methodology are contained in the project report (*4*) and in a TRB report (*6*).

Subjective Testing of Interior Noise Recordings

Twenty test sites were selected across the ranking of interior noise, with 10 above the median and 10 below the median interior noise level. The recorded sounds were transferred to a compact disc (CD) to allow randomization of the noise recordings. The comparator was selected as Wisconsin's interim random transverse tining standard, with an interior noise about halfway between the loudest and quietest pavements.

Twenty-four human subjects were used to rate the "noisiness" of 20 road surfaces. Subjects ranged in age from 20 to 39 years old (mean = 24.5). All subjects had normal hearing, defined as hearing thresholds less than or equal to 15 dB HL (hearing level) at the audiometric frequencies of 500, 1000, 2000, 3000, and 4000 Hz.

Sound-level measurements and audio recording of the interior noise level present while driving over different road surfaces in the Ford Taurus at 96 km/h (60 mph) were collected. Then 5-s samples of the digital audio recordings were transferred to a CD. Each 5-s sample was preceded by a 5-s sample of Road Surface 21 (the comparator).

The audio recordings were played back using a CD player (Sony CDP-291) and were transduced to the subjects through speakers with a flat frequency response. The presentation level (in dB) was controlled using a clinical audiometer (GSI 16) and was adjusted to reflect the measured interior noise level in dB(A) using a sound-level meter (Quest 155).

The relative "noisiness" of the road surfaces was determined using direct magnitude estimation. With this method, which theoretically results in a ratio scale, each of a set of stimuli is compared to a point on an internally generated scale, or continuum, for the attribute being rated—in this case, noisiness.

Using direct magnitude estimation, subjects rated the "noisiness" of each road surface by comparing it to the "noisiness" of Road Surface 21 (the standard comparator). The noisiness of the standard/comparator was given an assigned value of 100 points. If, for example, a subject judged the noisiness of a road surface to be twice as noisy as the standard, then the subject would assign it 200 points. If, on the other hand, the subject judged the noisiness of a road surface to be half as loud as the standard, then the subject would assign it 50 points. Subjects could use any point assignment they wanted and did not have to limit themselves to fractions or multiples of the 100 points assigned to the noisiness of the standard. They could use any assignment they chose if it represented their judgment of the relative noisiness of the road surface to the noisiness of the standard.

All subjects were given a training session to familiarize them in using direct magnitude estimation to make relative judgments. Each subject listened to the 20 road surfaces twice. Presentation of the road surfaces was randomized within and among the subjects. The data obtained during the second listening trial were averaged across subjects and were used to rank the "noisiness" of the road surfaces using the resulting ratio scale.

ANALYSIS

Exterior Noise

The noise data were analyzed separately for each of the pavement parameters. The noise levels and the frequency of the discrete tone increased with speed. In this report, only the data corresponding to 96 km/h (60 mph) are presented for conciseness. Pavements are ranked by exterior noise (L_{MAX}) and are shown in Table 1.

Transverse PCC Pavement Texturing

Figures 1 and 2 compare FFT frequency spectra measured for the transverse-tined concrete pavements with different spacings and tine depths. These spectra exhibit a shape similar to the ⅓-octave band spectra that were collected during the Phase I study for similar pavements. At the same time, these FFT spectra provide much better frequency resolution with regard to identification of frequencies characteristic of the transverse-tined pavements. These characteristic frequencies depend on the tine spacing and the vehicle speed. When the spacing increases, these frequencies decrease (shift left) for the surfaces with uniform spacing, as shown in Figure 2.

An analysis of the effect of the tining depth for two of the 13-mm sections (Iowa No. 1 and Wisconsin No. 9) showed that the texture with the 3- to 5-mm tining depth (in Iowa) exhibited 1 dB(A) higher overall noise levels than the 1.5-mm-deep Wisconsin section, for all of the three car speeds tested. The Iowa 1 section also had a wider tine width than Wisconsin No. 9 (5.1 mm versus 3.5 mm).

The transverse pavements with saw cuts, both with regular (Iowa No. 9) and random (Colorado No. 5) cuts exhibited characteristic frequencies, which were detected within "unexpected" frequency ranges. These frequencies apparently were a function of the saw cut's configuration or geometry. Both had deep textures with wide tine widths (ROSAN ETD > 1.0).

Transverse PCC Texturing with Random Tining

Figure 3 compares four different transverse PCC pavements with random tining. The 38-mm Minnesota pavement, No. 4, and the truly random Wisconsin pavement, R2 (25 mm), are characterized by significantly better acoustical qualities than the 19- and 25-mm new Wisconsin pavements, Nos. 1 and 2. The Minnesota surface still has a characteristic peak of 7 to 8 dB at approximately 700 Hz that does not significantly affect the A-weighted level.

Random Skew Tining

Figure 4 shows two new Wisconsin pavements, Nos. 5 and 7, with the 19-mm skewed random tining. Both pavements demonstrate good acoustical qualities for the random textures, without any significant characteristic peaks in their noise spectra. In the frequency range of 800 to 1500 Hz, the 1:6 skewed pavement is characterized by lower SPLs than the 1:4 texture. Both have ROSAN ETD slightly over 0.700. Both pavements were skewed left-hand forward (LHF), which indicates that the tining pattern is changed from transverse by advancing the left side of the tining rake in the direction of traffic flow.

Longitudinal and Special PCC Pavements

Similar to the Phase I study, no characteristic frequencies were found for longitudinal and special PCC pavement textures. Many of the longitudinal tined pavements had low exterior-noise levels.

The Skidabrader pavement in Wisconsin, No. 16, has an acceptable acoustical performance at lower and higher frequencies. However, at frequencies between 400 and 1000 Hz, this texture loses its advantage. The milled pavement (Iowa, No. 8) has a very similar acoustical spectrum, while the ground pavement (Wisconsin, I-43, No. 5) is characterized by a better performance in the same frequency range. The ground pavement was approximately 3 dB(A) quieter in overall SPL compared with the other special PCC. A 1998 study (*7*) of diamond grinding on a relatively new uniformly transverse-tined PCC pavement in Minnesota showed a reduction of the L_{10} sound level of 2 to 3 dB.

TABLE 1 Ranking of All Test Sections by Exterior Noise (L_{MAX}), Car at 96 km/h (60 mph)

State	Road	Section	Texture	Lmax
Wisconsin	I-43	3	Std. ACP	78.9
Iowa	I-163	3	19mm uniform long. (1.5 mm d)	79.0
Colorado	I-70	7	19mm uniform long. saw cut	79.6
Iowa	I-163	4	19mm uniform long. (1.5 mm d)	79.9
Wisconsin	I-43	2	Std. ACP	79.9
Wisconsin	I-43	6	SMA, 9mm stone	80.5
Colorado	I-70	9	19mm uniform long.	80.9
North Dakota	I-94	F	Trans., var., 26,51,76,102mm	81.0
Wisconsin	I-43	1	SHRP ACP	81.1
Wisconsin	I-43	5	Ground PCCP	81.2
North Dakota	I-94	H	19mm uniform long.	81.5
Wisconsin	STH 29	6	25mm uniform long.	81.5
Wisconsin	I-43	4	SMA, 16mm stone	81.6
Minnesota	US 169	1	19mm uniform long.	81.7
Wisconsin	STH 29	9	13mm uniform trans., (1.5mm d)	81.9
Wisconsin	STH 29	9a	13mm uniform trans.	82.1
North Dakota	I-94	G	13mm uniform trans.	82.2
New Wisconsin	STH 29	5	19mm random skew 1:6, LHF	82.4
Minnesota	US 55	4	38mm random trans.	82.6
New Wisconsin	STH 29	8	25mm random long.	82.7
North Dakota	I-94	A	25mm uniform skewed 1:6, RHF	82.7
Iowa	I-163	1	13mm uniform trans. (3-5mm d)	82.8
Colorado	I-70	4	13mm uniform trans.	83.0
North Dakota	I-94	B	19mm uniform trans.	83.0
New Wisconsin	STH 29	7	19mm random skew 1:4, LHF	83.1
Iowa	I-163	2A	19mm uniform trans., (IA. Std.)	83.3
Wisconsin	US 151	R2	25mm random trans. (Zignego)	83.4
New Wisconsin	STH 29	6	25mm random skew 1:4, LHF	83.5
Minnesota	US 169	7	LTD only	83.7
North Dakota	I-94	I	25mm uniform trans.	83.7
Iowa	I-163	8	Milled PCCP	83.8
New Wisconsin	STH 29	4	25mm random skew 1:6, LHF	83.8
Wisconsin	STH 26	R3	25mm random trans. (Trierweiller)	83.8
Minnesota	US 12	3	19mm random trans.	83.9
New Wisconsin	STH 29	10	25mm uniform long.	83.9
Wisconsin	STH 29	11	Manuf. random trans.	83.9
Wisconsin	STH 29	8	25mm uniform skewed 1:6, LHF (1.5mm d)	83.9
Wisconsin	STH 29	10	19mm uniform trans.	84.0
Colorado	I-70	5	Random trans. saw cuts (16,22,19 mm)	84.1
Minnesota	US 169	8	19mm Unif. Long.	84.3
Colorado	I-70	3	Random trans. (16,22,19 mm)	84.4
Iowa	I-163	9	13mm uniform trans., sawcut	84.6
Wisconsin	STH 29	16	Skidabrader, PCCP	84.6
Wisconsin	US 51	R1	25mm random trans. (Vinton)	84.8
Minnesota	US 169	2	19mm random trans.	84.9
New Wisconsin	STH 29	9	19mm random long.	85.3
Wisconsin	STH 29	R0	21mm truly random trans.	85.4
Iowa	I-163	5	19mm random trans. (3-5 mm d)	85.5
New Wisconsin	STH 29	2	19mm random trans.	86.3
Wisconsin	STH 29	15	25mm uniform trans.	86.3
Colorado	I-70	1	25mm uniform trans. (CO. Std.)	86.4
New Wisconsin	STH 29	1	25mm random trans.	86.6
New Wisconsin	STH 29	3	25mm uniform trans.	86.6
Minnesota	US 169	6	38mm random trans.	87.3

All tined PCC surfaces are 3 mm deep unless otherwise specified.

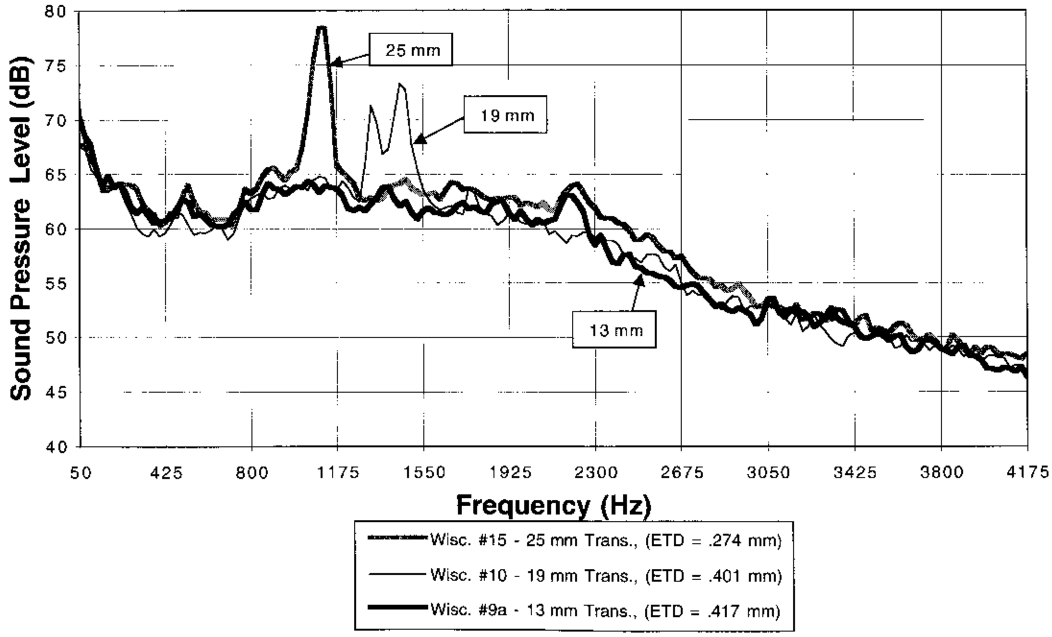

FIGURE 1 Comparison of exterior noise of uniform transverse-tined PCC pavements.

Asphalt Pavements

The stone, mastic, asphaltic (SMA) pavement provides the best acoustical qualities at frequencies higher than 2000 Hz, and the WisDOT standard dense-graded asphalt (AC) is better for the 500- to 2000-Hz range. The Strategic Highway Research Program pavement did not show any advantages over standard dense pavements.

When comparing SMA pavements with 9-mm (3⁄8-in.) and 16-mm (5⁄8-in.) stones, the pavement with smaller aggregate (less texture) shows better acoustical qualities for all three speeds tested.

Comparison of Pavement Friction, Texture Depth, Tining Width, and Exterior Noise

Regression analyses were performed between friction (FN_{40}, B or bald), texture depth, tine width, and exterior noise (L_{MAX}) as the dependent variable for all pavement types. The correlations were low and inconclusive (*4*). A regression analysis also was performed between the ROSAN-developed tine depth and tine width. The analysis, with an R^2 of 0.83,indicated that tine width is dependent on tine depth (*4*).

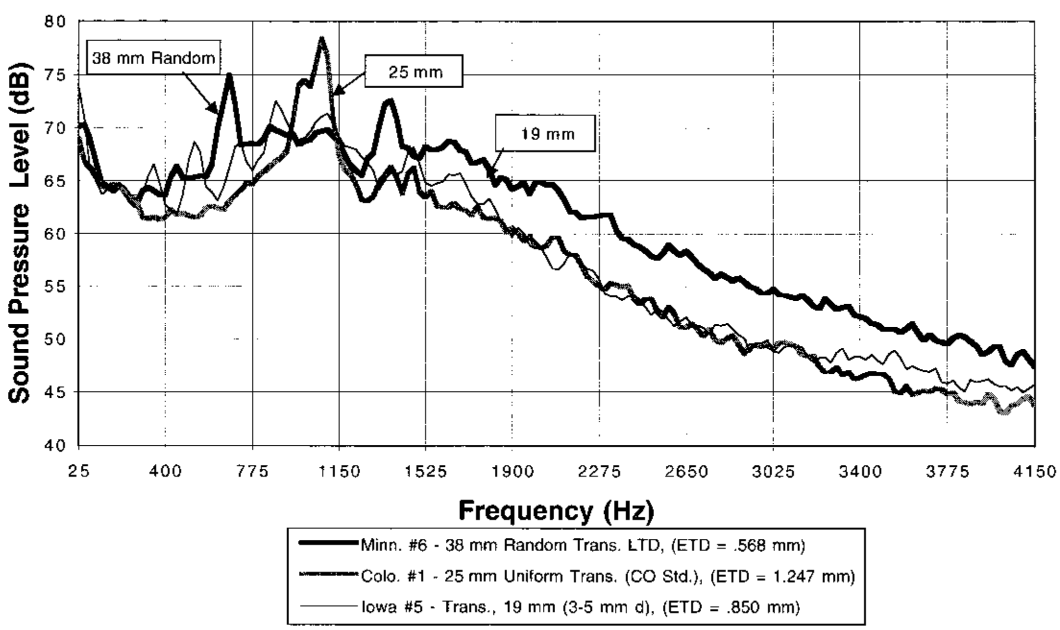

FIGURE 2 Comparison of exterior noise of uniform and random transverse-tined PCC pavements.

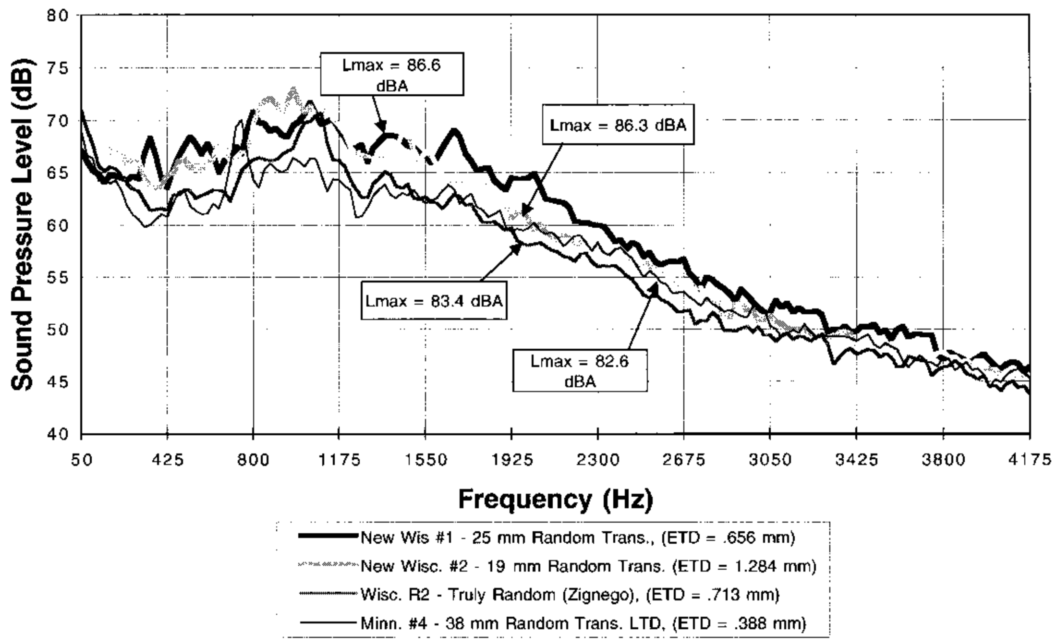

FIGURE 3 Comparison of exterior noise of random-tined PCC pavements.

Interior Noise

Ranking of All Test Sections and Noise Comparisons

All test sections were ranked based on interior noise (L_{eq}) with the car at 96 km/h (60 mph) and are shown in Table 2.

The uniform, transverse-tined concrete pavements generated discrete frequencies inversely proportional to the tine spacings. The frequency spectra of the transverse random textures were clearly dependent on a randomization pattern.

The 38-mm Minnesota pavement, No. 4, shown in Figure 5, contained characteristic first and second harmonic peaks at approximately 700 and 1400 Hz, which was not observed for the Wisconsin

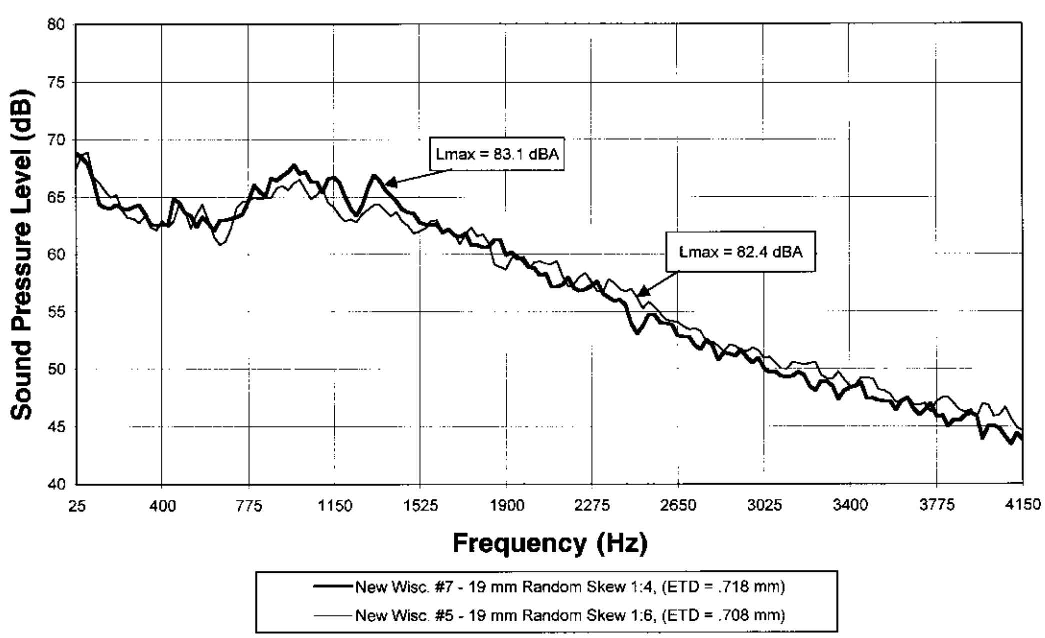

FIGURE 4 Comparison of exterior noise of random skew tining on PCC pavements.

TABLE 2 Ranking of All Test Sections by Interior Noise (L_{eq}), Car at 96 km/h (60 mph)

State	Road	Section	Texture	Leq
Wisconsin	I-43 (WALW.)	3	Std. ACP	65.0
Wisconsin	I-43 (WAUK.)	1	SHRP ACP	65.9
Wisconsin	I-43 (WAUK.)	2	Std. ACP	66.0
Wisconsin	I-43 (WALW.)	4	SMA, 16mm stone	66.7
Minnesota	I-494	5	LTD only	66.8
Minnesota	MN 55	4	38mm random trans.	66.9
Iowa	I-163	3	19mm uniform long. (1.5 mm d)	67.2
Minnesota	US 169	1	19mm uniform long.	67.2
New Wisconsin	STH 29	7	19mm random skew 1:4, LHF	67.2
Michigan	I-75	1	European texture	67.5
Iowa	I-163	4	19mm uniform long. (3-5 mm d)	67.6
New Wisconsin	STH 29	5	19mm random skew 1:6, LHF	67.6
North Dakota	I-94	A	25mm uniform skewed 1:6, RHF	67.6
Wisconsin	I-43 (WAUK.)	6	SMA, 9mm stone	67.6
New Wisconsin	STH 29	4	25mm random skew 1:6	67.7
North Dakota	I-94	F	Random trans., var., 26,51,76,102mm	67.7
New Wisconsin	STH 29	8	25mm random long.	67.8
New Wisconsin	STH 29	10	25mm uniform long.	68.0
Colorado	I-70	7	19mm uniform long. saw cut	68.1
Iowa	I-163	1	13mm uniform trans. (3-5mm d)	68.2
Iowa	I-163	2A	19mm uniform trans. (IA. Std.)	68.2
Minnesota	US 169	7	LTD only	68.3
Colorado	I-70	9	19mm uniform long.	68.4
Minnesota	US 12	3	19mm random trans.	68.4
Michigan	I-75	2	25mm uniform trans. (MI. Std.)	68.5
New Wisconsin	STH 29	6	25mm random skew 1:4, LHF	68.5
North Dakota	I-94	B	19mm uniform trans.	68.5
North Dakota	I-94	G	13mm uniform trans.	68.5
North Dakota	I-94	I	25mm uniform trans.	68.5
Colorado	I-70	5	Random trans. saw cuts (16,22,19 mm)	68.6
Wisconsin	US 151	R2	25mm random trans. (Zignego)	68.6
New Wisconsin	STH 29	2	19mm random trans.	68.7
North Dakota	I-94	H	19mm uniform long.	68.7
New Wisconsin	STH 29	3	25mm uniform trans.	68.8
Wisconsin	STH 29 (EB)	R0	21mm truly random trans.	68.8
Minnesota	US 169	2	19mm random trans.	68.9
New Wisconsin	STH 29	1	25mm random trans.	68.9
Wisconsin	STH 26	R3	25mm random trans. (Trierweiler)	68.9
Wisconsin	STH 29	9	13mm uniform trans., (1.5mm d)	69.0
Wisconsin	STH 29	10	19mm uniform trans.	69.1
Iowa	I-163	9	13mm uniform trans., saw cut	69.2
Wisconsin	I-43 (WALW.)	5	Ground PCCP	69.2
Wisconsin	STH 29	6	25mm uniform long.	69.2
Wisconsin	STH 29	9a	13mm uniform trans.	69.3
Colorado	I-70	4	13mm uniform trans.	69.4
Minnesota	US 169	6	38mm random trans.	69.4
Minnesota	US 169	8	19mm uniform long.	69.4
Wisconsin	STH 29	8	25mm uniform skewed 1:6 LHF (1.5mm d)	69.4
Wisconsin	US 51	R1	25mm random trans. (Vinton)	69.4
New Wisconsin	STH 29	9	19mm random long.	69.5
Wisconsin	STH 29	15	25mm uniform trans.	69.5
Colorado	I-70	1	25mm uniform trans. (CO. Std.)	69.7
Colorado	I-70	3	Random trans. (16,22,19 mm)	69.9
Iowa	I-163	5	19mm random trans. (3-5 mm d)	70.0
Wisconsin	STH 29	11	Manuf. random trans.	70.2
Wisconsin	STH 29	16	Skidabrader, PCCP	70.6
Iowa	I-163	8	Milled PCCP	72.0

All tined PCC surfaces are 3 mm deep unless otherwise specified.

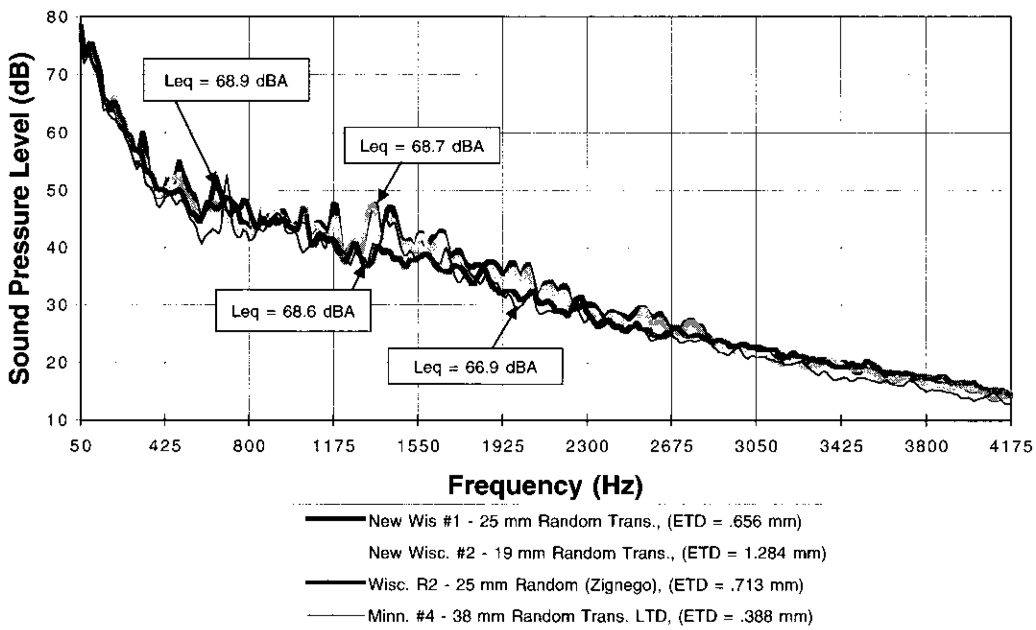

FIGURE 5 Comparison of interior noise on random-tined PCC pavements.

R2 truly random pavement. The examination of the ROSAN texture plots indicate that the 38-mm random of Minnesota No. 4 is close to uniform, and the ROSAN mean spacing is 31.5 mm.

Comparison of Pavement Friction, Texture Depth, Tining Width, and Interior Noise

Regression analyses were performed between FN_{40} B, ROSAN ETD, tine depth and width (from the ROSAN algorithm), and interior noise. The results were similar to the exterior noise regression analysis but with even lower *R* values (*4*). Again, this is insufficient for firm conclusions.

Subjective Noise

Table 3 shows the results of the subjective rating of the "noisiness" of the selected road surfaces using direct magnitude estimation. To determine the reliability of the data, a split-half method was used. The subjects were divided into two groups, each consisting of 12 subjects. Scale values (ratings) were computed from the estimates for

TABLE 3 Comparison of Subjective and Objective Evaluations of Interior Noise Levels

State	Road	Section	Texture	Subject	Interior dBA	PNLT	Exterior dBA
WI-N	STH 29	5	19mm Random Skew 1:6, LHF	1	67.6	82.9	82.4
WI-N	STH 29	7	19mm Random Skew 1:4, LHF	2	67.2	82.4	83.1
WI	I-43	1	SHRP ACP	3	65.9	81.8	81.1
ND	I-94	F	Random trans. var., 26,51,76,102mm	4	67.7	83.2	81.0
WI-N	STH 29	10	25mm uniform long.	5	68	82.6	83.9
MI	I-75	1	European texture	6	67.4	82.6	NA
MN	US 55	4	38mm random trans.	7	66.9	81.7	82.6
IA	I-163	9	13mm uniform trans., saw cut	8	69.2	85.2	83.3
IA	I-163	5	19mm random trans, (3-5mm d)	9	70	85.4	83.8
IA	I-163	8	Milled PCCP	10	72.1	88.4	84.6
IA	I-163	1	13 mm uniform trans. (3-5 mm d)	11	68.2	84.6	82.8
WI	I-43	5	Ground PCCP	12	69.3	85.9	81.2
WI-N	STH 29	1	25mm random trans.	13	68.8	83.1	86.6
CO	I-70	1	25mm uniform trans. (CO Std.)	14	69.7	86	86.4
WI	US 151	R2	25mm random trans. (Zignego)	15	68.6	84	83.4
WI	STH 29	9a	13mm uniform trans.	16	69.3	84.7	82.1
MN	US 169	6	38mm random trans.	17	69.4	84.3	87.3
WI	STH 29	10	19mm uniform trans.	18	69.1	84.7	84.0
CO	I-70	5	Random trans. saw cut (16,22,19mm)	19	68.6	84.7	84.1
WI	STH 29	15	25mm uniform trans.	20	69.6	85.3	86.3

PNLT - The tone-corrected, perceived noise level, which includes the effects of sound pressure level, frequency spectrum (including the presence of pure tone), and duration.

each group. A correlation between the two sets of scales exceeded 0.9, which suggests that the scale values are highly reliable.

It should be pointed out that the three newly constructed Wisconsin pavements were in the top six subjectively ranked pavements. These were the 19-mm random skew with both 1:6 and 1:4 skews (ranked 1 and 2, respectively) and the 25-mm uniform longitudinal (ranked fifth). The fourth-ranked pavement is a North Dakota random transverse, and the sixth-ranked is Michigan's European Texture (both with ROSAN ETD below 0.6). Unfortunately, the number of sounds (and hence pavements) that a person could listen to at one sitting is limited; therefore, only 20 pavements could be compared.

Comparison of Subjective and Objective Results

The AC and PCC pavements were ranked from quieter to louder according to the results of the subjective evaluations. Table 3 contains calculated interior and exterior A-weighted SPL and tone-corrected perceived noise level (PNLT) values. An attempt was made to compare (correlate) these values with the results of subjective evaluation. Little correlation was found between A-weighted and subjective rankings when all of the pavements were used. Similarly, PNLT values did not correlate with the subjective rankings, except for several uniformly tined pavements.

In general, PNLT is not a suitable metric for the evaluation of pavements. There are significant spectral differences between tire/pavement noise, for which the majority of the annoying frequency components lie within 700 to 2000 Hz, and the aircraft fly-over noise, for which this metric was developed.

Evaluation of Tonal Components

Based on the literature search, a methodology was developed to quantify the prominence of the tones generated by different transverse-tined pavements. According to the results of this analysis, transverse-tined textures, which generate objectionable discrete tones, can be characterized by their calculated prominence ratios based on the Fletcher-defined Critical Bandwidth. Such an approach seemed to reflect the expected annoyance due to the tonal character of the transverse-tined pavements (*8*).

RESULTS

Criteria for a "Desirable" Pavement

In reviewing the noise and textures of all 57 pavements, the research team used judgment to select desirable textures for further analysis and possible recommendations, based on all noise and texture characteristics of each of the test sections. Such textures would be characterized by the following:

- A maximum exterior noise level of 83.0 dB(A),
- A maximum interior noise level of 68.0 dB(A),
- A subjective noise rating of 100 or less,
- No predominant spikes or discrete frequencies, and
- A minimum ROSAN ETD of 0.7 or above.

Results Summary

The "best" (lowest) exterior noise levels in the texture type that could satisfy the above set criteria are compared in Figure 6. This includes Iowa No. 33 longitudinal, Wisconsin I-43 No. 4 (SMA with largest aggregate), the new Wisconsin No. 5 random skew, and the best random transverse (Wisconsin R2). What is striking is the closeness of the only AC pavement with texture comparable to PCC pavements (Wisconsin No. 4) to that of the longitudinally and skewed tined PCC pavements. All have ROSAN ETDs above 0.7, with the Iowa No. 4 longitudinal having the deepest texture (ROSAN ETD of 1.253) and the lowest exterior noise of the four. This could mean that depth is not a factor in noise characteristics of longitudinally tined pavement.

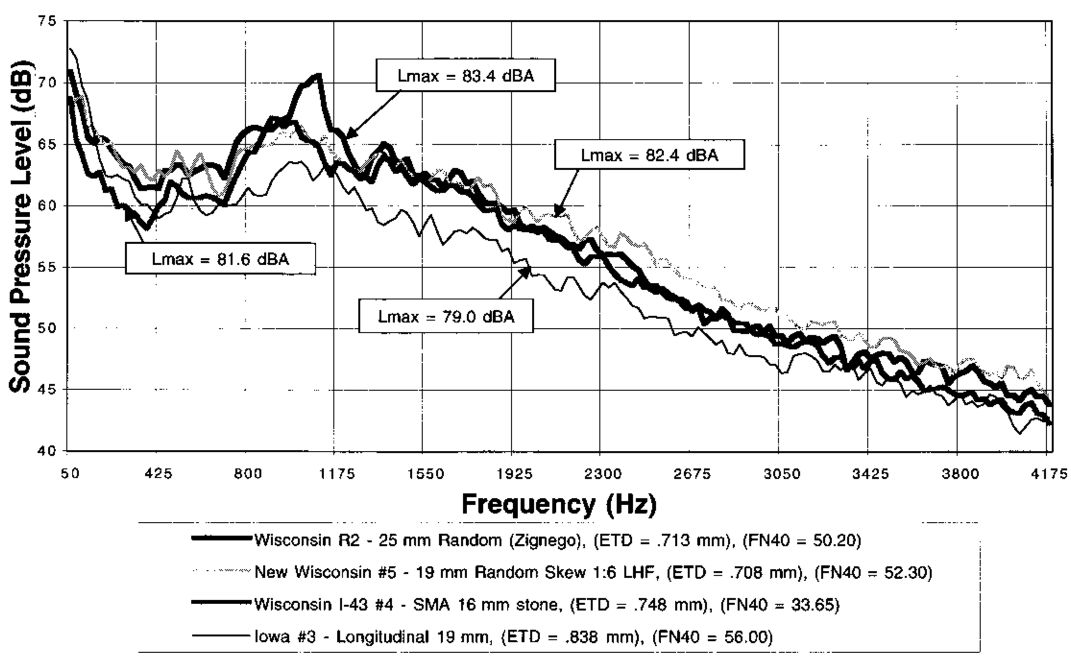

FIGURE 6 Comparison of exterior noise for the "best" of the different pavement texture types.

The same four textures are very close to meeting the criteria for interior noise, also. Similarly, the "best"(lowest) interior noise levels by texture type are shown in Figure 7.

CONCLUSIONS

- Uniform transverse tining exhibits discrete frequencies that coincide with calculated locations on the sound spectrum based on tine spacing and vehicle speeds. This causes the whine that most drivers find to be obnoxious.
- Little correlation was found between either exterior or interior noise and texture depth (ROSAN ETD or mean tine depth). This is believed to be due to the great variation in texture depth in all states and is contrary to the conclusions of Phase I of this study. However, those pavements with the widest and deepest texture were often among the noisiest. Because deeper tining generally produced a wider tine, it is impossible to conclude which of these two parameters influences pavement noise more.
- Both uniform and random transverse tining provide higher exterior and interior noise levels than skewed or longitudinally tined PCC pavements.
- The prominence ratio technique can be used to assess noise quality of uniformly spaced transverse textures. Neither PNLT metric nor D-weighting scale is suitable for evaluation of the tire/pavement noise with tonal components.
- The AC pavements, the longitudinal tined and random skewed PCC pavements, and the European texture exhibit the lowest interior noise levels, based on both the objective and subjective assessments.
- Colorado's test sections were constructed with the greatest tining width and texture depth and were among the noisiest. This reinforces the hypothesis that, as width and texture depth increase, so do both interior and exterior noise.
- A longitudinally tined PCC is as quiet as or quieter than some AC pavements. It can be constructed easily, the tire/pavement noise did not create any prominent discrete frequencies, and it received good subjective ratings.
- Random skewed (1:6) textured pavements can be constructed relatively easily, exhibit low interior noise and no discrete frequencies, and have the best subjective ranking. They have higher levels of exterior noise than longitudinal tined PCC and AC pavements, but lower than random transverse PCC pavements.
- Random transverse textured pavements are very sensitive to spacing patterns. When spacing tends to be more uniform, discrete frequencies may still develop. This can cause objectionable whine.
- The ground PCC pavement, although not as quiet as other PCC pavements, exhibited no predominant frequency or spike. A recent project comparing before and after noise measurements on recently constructed random transverse-tined pavement in St. Paul, Minnesota, showed a noise reduction of 2 to 3 dB (L_{10}) after diamond grinding.

RECOMMENDATIONS

1. A study of wet-pavement accidents should be conducted using current accident data and comparing longitudinal and transverse-tined pavements to determine what texture and friction values will provide the necessary safety and minimize noise. The current guidelines for tining depth are not being achieved uniformly in any state studied. The impact that this has on safety is unknown.
2. If overall noise considerations are paramount, longitudinal tining that provides satisfactory friction should be considered. A spacing of 19 mm uniform tining will provide adequate friction. It also should comply with current FHWA guidelines and, according to other studies, it will minimize any effects on small-tired vehicles.
3. If subjective perceptions and texture considerations are paramount, a random-skew 1:6 textured pavement that is offset the opposite of the skew for the sawed joints may be used to achieve the friction of a transverse pavement and most of the noise benefits of the longitudinal pavement, with no discrete tones.

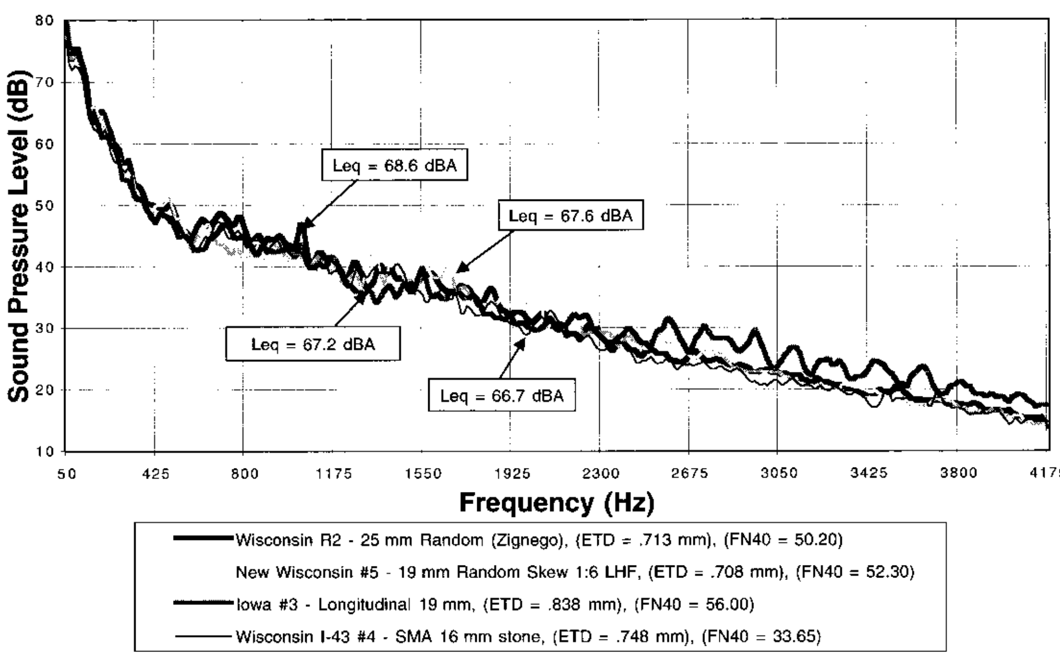

FIGURE 7 Comparison of interior noise for the "best" of the different pavement-texture types.

4. If texture considerations are paramount, and a skewed pattern is impractical, randomly tined pavements should be used. They should be carefully designed and built, using a highly variable spacing. A tining rake of at least 3 m (10 ft) long should be used.

5. Diamond grinding, if sufficiently deep to remove the transverse texture, can be considered a treatment for PCC pavements with excessive whine.

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