# TIRE PAVEMENT NOISE AND SAFETY PERFORMANCE PCC SURFACE TEXTURE TECHNICAL WORKING GROUP

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## 1. TECHNICAL WORKING GROUP SUMMARY

A Technical Working Group (TWG) representing State Highway Agencies, industry, academia, and the Federal Highway Administration (FHWA) met over a three year period to update guidance on methods to obtain high pavement surface friction values while minimizing tire / pavement noise. The input provided to the authors by the TWG members during the development of this updated guidance was greatly appreciated. The need for this guidance was based on a number of complaints about tire / pavement noise (high-pitched whine and/or low-pitched rumble) from occupants of adjacent residences and from motorists driving over transverse tined pavements. Also, some State legislatures are mandating corrective actions for sections of roadway deemed to have objectionable noise levels. These complaints have raised concerns about the adequacy of existing guidance to assure adequate friction characteristics while minimizing tire / pavement noise. An existing FHWA Technical Advisory (T 5140.10) will also be updated in the near future. The update will reflect the results of this effort and of additional testing and evaluations being conducted in 1997 and 1998 to verify the recommendations made and to resolve some technical issues where existing research data appears to provide conflicting results.

The work plan developed with the assistance of TWG was finalized in early 1994 and called for review of current guidance on surface texture as it relates to:

- safety (friction and vehicle control including effects of splash and spray)
- noise (inside and outside of the vehicle)
- drainage (cross slope, effect of longitudinal and transverse tining, and other surface textures)
- durability
- ride (profile)
- texture quality (measurement)
- economy of construction

The plan also called for a literature search of previous research efforts in the U.S. and abroad, and close monitoring of current U.S. and foreign research.

The FHWA Office of Highway Operations Research and Development provided major technical assistance by providing equipment and technicians to obtain texture depths by the FHWA texture van, the texture beam, the sand patch test, and the static drainage (outflow meter) test on a variety of State test sections in 1994 and 1995. In 1997, they continued that cooperation by loaning the ROad Surface ANalyzer (vehicle based) $ROSAN_v$ to the Wisconsin researchers. This newly developed equipment, mounted on a standard minivan, measures pavement texture at highway speeds along a linear path.*(1)* Special procedures will be needed to measure longitudinally oriented textures.

On November 1, 1995, FHWA issued a policy statement on PCC Surface Texturing that included a preliminary summary of the TWG's findings. The final report of the TWG, FHWA-SA-96-068, dated May 1996 was published and distributed by a November 12, 1996 memorandum to Regional Federal Highway Administrators. The Executive Summary (pages v through ix of the final report) updated the preliminary guidance furnished.*(2)* This paper summarizes the major findings of that effort and reflects some more recent developments.

As part of this effort, PCC pavement surface texture projects (friction and/or noise studies) were constructed or revisited in Arizona, California, Colorado, Iowa, Michigan, Minnesota, North Dakota, Virginia, and Wisconsin. Each of these States furnished draft or final reports, including experimental data relating to friction and/or noise, during 1995 or prior years. A summary of their efforts and findings to date (except for Arizona) are located in the next section.

Arizona conducted a noise inventory that compared traffic noise generated from asphalt rubber friction courses and tined or grooved PCC pavements. However, no corresponding data on skid resistance or total or wet weather accident rates were considered. The consultant's report, FHWA-AZ96-433 dated February 1996, "*A Comparison of Traffic Noise from Asphalt Rubber Asphalt Concrete Friction Courses (ARACFC) and Portland Cement Concrete Pavement (PCCP)*" has been published.

Current guidance on surface texturing for safety are given by:

- Surface Finishing of Portland Cement Concrete Pavement (PCCP), W. H. Weseman's memorandum to FHWA Regional Administrators, November 1, 1995
- 23 CFR 625—Design Standards for Highways
- FHWA Technical Advisory T 5040.17, Skid Accident Reduction Program, December 23, 1980
- *Guidelines for Skid Resistant Pavement Design*, AASHTO, 1976
- FHWA Technical Advisory T 5140.10, Texturing and Skid Resistance of Concrete Pavements and Bridge Decks, September 18, 1979 (to be updated)
- FHWA Technical Advisory T 5040.28, Developing Geometric Design Criteria and Processes for Nonfreeway RRR Projects, October 17, 1988
- Title 23 Code of Federal Regulations [(CFR) 500.205(d)], December 1, 1993, and non-regulatory supplement published on October 5, 1995 (Transmittal 14, Federal-Aid Policy Guide)
- 23 CFR 635.505(a), Interstate Maintenance Guidelines
- Highway Safety Grant Management Manual [particularly 23CFR Part 1251—State Highway Safety Agency (4/1/94) and Uniform Guidelines for State Highway Safety Programs (7/18/95) - especially Guideline No. 21], which replaced 23 CFR 1204.4, Highway Safety Guidelines (Highway Safety Program Guideline No. 12—Highway Design, Construction, and Maintenance) on October 5, 1995 (Federal Aid Policy Guide Transmittal 14)

Current noise guidance and technical publications on pavement friction and noise related issues include:

- Highway Traffic Noise Guidance and Policies and Written Noise Policies, Tony Kane's June 12, 1995, memorandum to FHWA Regional Administrators, 86 pp.
- *Guide on Evaluation and Abatement of Traffic Noise*, AASHTO, 1993, 40 pp.
- ACI 325.6R-88, Texturing Concrete Pavements .
- S. H. Dahir and J. J. Henry, *Alternatives for the Optimization of Aggregate and Pavement Properties Related to Friction and Wear Resistance*, FHWA-RD-78-209, Final Report, FHWA, April 1978, 295 pp.
- W. E. Meyer, *Synthesis of Frictional Requirements Research*, FHWA/RD-81/159, Final Report, FHWA, June 1982, 96 pp.
- Fifth International Conference on Concrete Pavement Design and Rehabilitation, Volumes I and II, Purdue University, April 1993, 700 pp.
- C. L. Wu and M. A. Nagi, Optimizing Surface Texture of Concrete Pavements, Portland Cement Association Research and Development Bulletin RD111T, PCA, Skokie, IL, 1995, 108 pp.

### Foreign Research or Publications

European, Australian, and South African research in this area have been ongoing for several years. A number of significant reports have been produced that were used to support the findings and recommendations made in this report. A brief summary of some of the more recent publications is provided in a later section.

### Related National Cooperative Highway Research Projects

Several NCHRP studies are now in progress that will be of significant help in providing answers to surface texture safety and noise issues:

- NCHRP 1-29, Improved Pavement Surface Drainage, is now being published, and is expected to consider the effect of longitudinal grade, cross slope, and surface texture (average texture depth and also longitudinal versus transverse tine texture on PCC pavements) on surface drainage and safety.
- NCHRP Synthesis of Highway Practice, Topic 26-05, "Relationship of Pavement Surface Texture and Highway Traffic Noise," is underway and the second draft of the report was reviewed by the project panel in July 1997.
- NCHRP Project 1-31, "Smoothness Specifications for Pavements," addresses some of the questions relating to measuring, specifying, and constructing smoother riding pavements. The final report is now available from NCHRP. NCHRP Project 10-47 will develop Guidelines for Longitudinal Pavement Profile Measurements including guide construction specifications and should be completed in 1998.

## 2 U.S. RESEARCH STATUS

**A summary of the experimental studies underway or recently completed in the various States is presented in this section. An expanded summary for each State, including data tables, is located in appendix B of FHWA-SA-96-068, dated May 1996 which has been distributed by FHWA to the various States and Technology Transfer Centers. Results and findings obtained from all the test sections are based on States reporting as of April 1, 1996, except as noted.**

**California:** In 1994, two 17-year-old test sections were retested using a standard ASTM E-274 skid trailer for friction values. Test section number one has a transversely tined texture that has been heavily traveled, and test section number two has a longitudinally tined texture that has been moderately traveled. The most interesting result was the high ribbed (E-501) and smooth (E-524) tire friction numbers (over 40) on the longitudinally tined texture (spaced at 19 mm) for speeds of 96 km/h. California requires 30 percent siliceous sand in its PCC mix and requires a minimum friction of 0.30 as measured by its standard test procedure. Also, the retest showed lower friction numbers for both the 13 mm spaced transverse and 13 mm spaced longitudinal tining sections compared to the test sections with 19 mm tine spacing.*(3,4)*

**Colorado:** An experimental project on I-70 east of Denver has nine different texture sections. Friction, noise, texture, and profile tests were taken just before the pavement was open to traffic in October 1994, and then again in June 1995. The first finding was unusual in light of other findings around the country: The variable (16 mm-22 mm-19 mm) transverse tining had the highest friction values for the smooth and ribbed tires, but it was also the noisiest section. The main reason for the high noise level is believed to be that the variable transverse tining had the highest texture depth of 1.72 mm. Friction and noise values behaved in a similar pattern for the variable (16 mm-22 mm-19 mm) transversely grooved (hardened concrete) section. This grooved section had an average texture depth of 1.24 mm. The section with the lowest noise also had the lowest friction number and was the longitudinally astro-turf dragged section. This section also had the lowest average texture depth of 0.38 mm. The longitudinally tined section produced a low-noise level and maintained a friction number above 36 with a smooth tire at 96 km/hr. The average texture depth was 0.64 mm for this section. The large differences in average texture depth, as measured by the sand patch test in 1995, make a direct comparison of the various textures difficult. *(5)*

**Iowa:** A test section consisting of seven textures was constructed late in 1993. Also, there are nearby sections of concrete pavement that have been retextured longitudinally by a modified carbide milling machine or transversely by grooving the hardened concrete with diamond saw blades. Friction tests using an ASTM E274 two wheeled trailer with a ribbed tire on the wetted surface at 64 kmph have now been conducted in 1994, 1995, and 1996. The test results ranged from 45 to 56 in 1996 indicating satisfactory friction. A subjective noise evaluation was performed in 1996. The transverse tined textures were all deemed to generate objectionable noise. The longitudinally tined textures generated substantially less objectionable noise. The August 1996 Final Report (MLR-93-4) recommended Iowa DOT change their specifications to require 3 mm to 5 mm deep longitudinal tine texturing and to require controls to ensure the straightness of the longitudinal tining.*(6)* A method has been developed to produce a mold of the existing pavement texture using plastic material and food coloring. The mold has been effectively used to illustrate to contractor and inspection personnel the surface texture desired.

**Michigan:** A 2 km section of pavement with an exposed aggregate surface treatment (constructed of a high-quality two-layer concrete mix-hybrid German/Austrian design) was constructed in 1993 adjacent to a 2 km section of pavement with Michigan's standard concrete mix design and its standard transversely tined (26 mm spacing) texture. Noise measurements taken in 1993 and 1994 showed very little difference in total noise output or third octave band frequencies between the two sections. The Michigan section had friction values considerably higher (about 10 friction numbers) than the European design, although both sections had acceptable values. The initial lower friction values of the European design are believed to be related to the inexperience of the contractor with this type of construction and to the 0 to 5 mm sand (Michigan standard) rather than the 0 to 1 mm sand used in the Austrian specifications.*(7,8)*

**Minnesota:** Two existing test sections (originally tested in 1987) were retested for exterior noise and friction values. Both test sections consisted of various transversely tined PCCP textures and dense-graded AC pavements. The exterior noise values were split into their noise spectra frequency range. The quietest sections were the AC pavement and the 26 mm spaced transversely tined PCC pavement. **Based on the noise spectra results, it was concluded that noise frequency can differ greatly from one texture to the next without a change in the overall total noise. This is a highly significant finding and highlights the inadequacy of the highway noise measurement and analysis procedures previously used for detecting annoying tonal characteristics.***(9)*

**North Dakota:** Nine test textures were constructed in 1993 on I-94 at Eagles Nest. The textures were tested for exterior tire / pavement noise and interior vehicle tire / pavement noise. The interior tire / pavement noise tests are unique to other tests because four different vehicles were used to collect the data. Results, so far, are that the skewed tining and variable spaced tining produce the lowest outside tire / pavement noise. The North Dakota study concluded that there is no significant advantage for the transversely tined, longitudinally tined, or skewed tined texture in terms of interior vehicle noise. The 1995 test results concluded all the tining sections have good skid numbers (above 35 with a ribbed tire). Also, it was noted that the closer tine spacings (19 to 25 mm) appear to be the quietest.*(10)*

**Virginia:** Skid and texture tests were performed on a 25-year-old section of longitudinally tined continuously reinforced concrete pavement on I-64, east of Richmond. The friction values (average over 40 for the ribbed tire) have held up very well during the pavement's lifetime, indicating the durability of the texture is good when constructed with high-quality materials. No wet weather accident data are currently available to compare the longitudinally tined texture with transversely tined textures used elsewhere in the State.*(11)*

**Wisconsin:** Two test sections are being studied under a major research project to quantify the impacts of the pavement surface texture on noise, safety, and winter maintenance requirements. The concrete texture test sections consist of longitudinally tined, transversely tined, skewed tined, and Skidabrader (shotblasted) sections. The bituminous sections consist of dense-graded, stone matrix, and SHRP mix design asphalt surfaces. Both sections were constructed in 1994 in different locations in the State. Exterior noise was measured with the pass by method using a car and a flatbed truck. Friction tests were performed with the ribbed and smooth tire at 65 km/h and 80 km/h. Winter maintenance operations were also observed on all the test sections.

After the exterior noise measurements [for third octave band analysis and for average total noise levels in dB(A)] were taken, empirical evaluations were made by observers in a car driven over the test sections and by subjects standing on the roadway shoulder. The empirical evaluations did not match the objective measurements on the transversely tined PCC pavements (except for the 39 mm uniformly spaced tines). It was determined that the tire / pavement whine needed to be defined through means other than evaluation of total noise. Interior noise measurements were performed on nine transversely tined PCCP sections, three ACP sections, and on a continuously diamond ground section during the fall of 1995, in cooperation with the Minnesota DOT. Three vehicles were used at two different speeds, with five tests run for each vehicle at each speed. A Larson-Davis Type 2900 2-channel, real-time acoustic analyzer was used in the Fast Fourier Transform (FFT) analysis mode to make the interior noise analysis.

The narrow band noise spectrum of the interior measurements were examined and a pattern was detected that indicates the annoying frequencies occurs in the 1,000 Hertz range. The peak sound pressure levels [up to 15 d(B)A] create a pure tone that is irritating to the human ear. In the third octave band analysis, these peaks are averaged into the surrounding noise and become invisible. As a result, the following preliminary recommendations *(12)* were made:

- randomly space the transverse tines from 10 to 40 mm (with no more than 50 percent of the spacings exceeding 25 mm)
- develop better quality control for the depth of tining
- continue to monitor noise on the existing test sections while constructing new test PCCP sections with a greater variety of transverse and longitudinal tine spacing and depths

**In June 1997, a Phase II research study was approved to continue the research completed in early 1997.** The project was approved as a part of FHWA's Test and Evaluation Project, TE 30, High Performance Concrete Pavement. This new study includes:

- Construction of ten additional test sections of PCC pavement on STH 29 west of Wausau, Wisconsin.
- Measurement of exterior and interior noise and texture characteristics (friction testing conducted by the respective State) of recently constructed sections of PCC pavements in Colorado, Iowa, Minnesota, North Dakota, and Michigan, most of which were included in the previous State research studies.
- Measurement of interior and exterior noise, friction and texture characteristics of the new test sections in Wisconsin. The noise measurement methodology based on the Fast Fourier Transform (FFT) will be attempted for exterior as well as interior noise measurements.
- Assessment of the public's perception of various noise/texture combinations by a panel of raters.
- Selection of the best texture or textures and their demonstration in 1998 at a national workshop and open house to be conducted near the recently constructed PCC pavement test sections in Wisconsin.
- Measurement of interior and exterior noise, friction and texturing characteristics of 14 previously constructed test pavements and three newly constructed PCC pavements by three different contractors that utilized the interim random tining standard in 1996.

## Summary of Tire / Pavement Noise Research Results from the United States

The following preliminary conclusions about tire / pavement noise are made from the noise study results in Colorado, Iowa, Michigan, Minnesota, North Dakota, and Wisconsin:

1. Uniformly spaced transverse tines, particularly those spaced over 26 mm, produce the most irritating tire / pavement noise. This is shown in the results from Minnesota (loudest 65 mm and 78 mm spacing), North Dakota (52 mm, 78 mm, and 104 mm spacing), and Wisconsin (39 mm spacing).

2. The Michigan project has, thus far, not shown a significant total noise or frequency distribution difference between the Michigan standard 26 mm uniformly spaced transversely tined texture and the European exposed aggregate texture. While acceptable, the exposed aggregate surface texture friction numbers are about 10 numbers lower than the standard Michigan transversely tined texture.

3. The Minnesota study found dense-graded bituminous pavement to be quieter than PCC pavement [more than 3 dB(A)] based on total noise. However, it should be noted that the average AC texture depth was significantly less than most of the PCC textures, which is the major reason for this difference. **Also, a study of the noise frequency spectrum indicated that total noise is not a true indicator of whether the noise is considered objectionable or not.**

4. The interior vehicle noise studies do not show a large range in the total noise levels from the different textures. It is the narrow band frequency distribution (pure tones) that is most significant in determining whether a particular texture results in objectional tire / pavement noise.

5. Using transverse and longitudinal tining together (cross hatching) produces consistently higher total noise based on Wisconsin's results (and Virginia's experience as reported in TRR Report 652).

6. The noise output from the tire / pavement interaction on PCC pavement changes as speed changes. The transverse plastic broom finish was the quietest in Wisconsin's test section at a pass by speed of 96 km/h, but the transversely tined (13 mm spacing) and Skidabrader textures were quietest at 112 km/h pass by speed for car and truck test vehicles, respectively.

7. Colorado's variable transversely tined texture was the loudest but also had the greatest average texture depth. However, Wisconsin found a transversely tined section outside of its test area whose tines had greater randomized spacing (repeated each rake pass) that reduced objectionable noise output significantly when compared to the State standard transverse tined texture. The specified randomness of the spacing and the construction quality are initial factors in determining the generated noise characteristics and, ultimately, the resulting level of annoyance to the human ear.

8. Colorado's transversely and longitudinally grooved sections (hardened concrete) are quieter than the tined sections (plastic concrete) with similar planned dimensions. The difference could be related to construction practices and emphasizes the need for increased attention to this important feature by project inspectors to verify that the desired texture is being obtained. The use of samples to demonstrate the texture desired would help promote construction uniformity for both the inspection and contractor personnel. Tire industry experts expected that the sharper saw grooved edges would be noisier than transversely tined grooves with similar depth, width, and spacing. This finding will be reevaluated during retesting planned for the summer of 1997 as part of the Wisconsin follow-up research effort. The same noise and texture measuring equipment will be used in Wisconsin as well as on many of the sections previously constructed in five other States.

## 3 SUMMARY OF FOREIGN RESEARCH

There has been a substantial amount of foreign research related to reducing tire / pavement noise. There are two primary concerns when reviewing this literature:

1. Safety appears to have been given minimal consideration when evaluating noise reductions.
2. The effect of surface texture on drainage does not seem to be considered (possibly because 2.5 percent cross slopes are frequently used).

The purpose of this section is to provide a comparison of foreign practices with those currently used in the United States. There were nine primary research reports considered during the initial review. Since that time, some additional European, Australian, and Japanese reports (which are not included here) have become available due to the widespread public concern regarding these issues. The reports reviewed included:

1. ***Roadside Noise Abatement*, Organization for Economic Co-operation and Development (OECD), 1995, 170 pages.**

   This is a comprehensive discussion of roadside noise abatement, including tire / pavement interaction. Minimal engineering data are presented on the effect of pavement texture on surface drainage, friction, or wet weather accident rates. Its primary focus is on noise abatement from an environmental point of view.

2. ***State-of-the-Art Report and Recommendations for Practice and Further Developments*, BRITE/EURAM Project BE 3415 (Surface Properties of Concrete Roads in Accordance with Traffic Safety and Reduction of Noise), October 1994.**

   This report describes a literature study, laboratory research, and specially constructed test track measurements by representatives of the Netherlands, Germany, and Spain. The researchers considered longitudinal tining and exposed aggregate PCC pavement as the most promising for a noise reducing surface. Porous concrete surfacing was considered to need further development before it could be used in large-scale construction. Further research was recommended for the use of smoother equipment, alternative noise and texture measurement methods, and additional low-noise concretes.

3. ***Measurements on Test Stretches*, Report No. 240/7, BRITE/EURAM Project BE-3415, Berlin Technical University, May 1994.**

   This report describes the measurements of texture, tire / pavement noise, and skid resistance at two German test locations. Measurements were made on test sections composed predominantly of longitudinally tined and exposed aggregate textures. Transversely tined sections were at a minimum because of the assumption that they are inherently noisier. Generally, the longitudinally tined and exposed aggregate sections were within 1 dB(A) of each other, while the transversely tined sections were about 3 dB(A) higher as measured with the pass by method. There was greater variation in the noise trailer results. The friction properties were highest for the exposed aggregate sections and lowest for the longitudinally tined sections. There was no correlation found between the friction and acoustic properties.

4. ***Concrete Pavement Manual: Design and Construction*, Roads and Traffic Authority, New South Wales, Australia, December 1991.**

This manual takes many of the British research findings and presents them in the form of guidelines for finishing PCC paving. Some of the major aspects of the manual are:

- Microtexture is the critical component for skid resistance at high speeds.
- Macrotexture is viewed as the primary means to remove water to take advantage of the microtexture at higher speeds.
- The effectiveness of the microtexture is largely dependent on the quartz sand content.
- The mortar is the critical component to ensure durability of the surface texture to maintain high friction values.
- Durability depends substantially on cement content, water/cement ratio, and effectiveness of curing.
- Within 80 km/h zones, longitudinal burlap drag with no transverse texture is specified.
- For rural concrete surfaces, a transversely tined finish is specified. Variable (random) tine spacing is used, and the tining operation is closely monitored to obtain the maximum texture.
- Flexibility must be provided in the tining rake so that individual tines can traverse large aggregate stones without disturbing the surface or dislodging them, and the rake should be hinged in such a way that variable pressure can be exerted to adjust for varying "average" surface hardness.
- Longitudinal grooving is viewed as unsatisfactory for both stopping distance and for rotational stability of a braked vehicle at high speeds.

5. **J. Nichols and D. Dash, "Australian Developments to Reduce Road Traffic Noise on Concrete Pavements," 5th International Conference on Concrete Pavement Design and Rehabilitation, Purdue University, April 1993, Volume 2, pages 99 to 106.**

PCC pavement surface textures were evaluated in this paper by examining those with the following variations: burlap drag length, tine depth, tine width, and tine spacing. The tine spacings used were 13 mm, 26 mm, and randomized at 10/14/16/11/10/13/15/16/11/10/21/13/10 mm. It was concluded that the quietest surface texture produced to date (light burlap drag with light transverse tine depth and a randomized, average 13 mm spacing) has acceptable skid resistance in terms of Sideways Force Coefficient and texture depth.

6. **J. C. Van Der Walt, et al., "Design Consideration and Findings of the Surface Texture Improvement on the Ben Schoeman Freeway," Fifteenth Annual Transportation Conference, Pretoria, South Africa, 1995.**

This report summarizes and references previous South African noise studies. A section of transversely broomed PCC pavement had a high accident rate. This report examines the problems with the pavement texture and investigates the possible solutions to the problem. Advantages and disadvantages for longitudinal and transverse tining are examined, along with various combinations of tine width, depth, and spacing. The report reached the following conclusions:

- Durable concrete mixes should be provided.
- Width and spacing of the grooves are critical parameters.
- Cross slopes on pavements wider than 12 m should be increased from 2 to 2.5 percent.
- Alternative methods to SCRIM should be looked at to measure skid resistance.

Additional South African studies are referenced in appendix H of FHWA-SA-96-068.

7. ***International PIARC Experiment to Compare and Harmonize Texture and Skid Resistance Measurements*, PIARC Technical Committee on Surface Characteristics C.1, 1995.**

This research report provides data allowing one to define an international scale of friction values called the International Friction Index (IFI). The objective of the experiment was to compare the many different measuring methods used around the world and develop relationships for converting results produced by the different devices to a common scale. The universal friction scale (see "golden curve" in appendix H of FHWA-SA-96-068) *(2)* requires measurements of the friction and texture of a surface for conversion to other device readings. **This is an excellent procedure and is recommended for widespread implementation in the U. S.**

8. **Session 8 Papers, "Noise Reducing Surfaces and Skid Resistance and Rideability," 7th International Symposium on Concrete Roads, Vienna, Austria, October 3-5, 1994, pages 81-178.**

This publication contains a variety of papers briefly describing noise and skid research in Europe (United Kingdom, Belgium, Netherlands, Spain, Germany, Austria, and Sweden), as well as Australia (New South Wales) and the United States (Michigan European Concrete Pavement Demonstration Project). Many of the details of construction and noise and skid testing are provided. These papers demonstrate the current state-of-the-art of constructing low-noise concrete pavements with good skid resistance. However, because these are usually short experimental sections, no wet weather accident data are provided which is the real test of surface texture effectiveness.

9. **Proceedings, XX$^{th}$ World Road Congress, Montreal, Canada, September 3-9, 1995 (Individual Papers of Committees and Working Groups: C1 Surface Characteristics; C7 Concrete Roads; C8 Flexible Roads; and General Report, Question IV, New Techniques for Pavement Strengthening and Maintenance), PIARC.**

The various reports summarize much of the current activity for managing and maintaining pavements, including noise and friction-related issues. In the C1 committee report, increasing exchange of information between road and vehicle engineers is reported. **Current efforts in Europe to develop standards for noise reduction of tires is being expanded to include a definition of road surface testing not only for noise but also for safety.** There is a major lack of data on wet weather accident rates in Europe as well as in the U.S. Evidence from the U.K., where a policy on enhancement of road texture has been in existence for some years, indicates that there is almost a five times payback in terms of reducing accidents. The policies being presented are based on accident risk ratings of specific sites.

Committee report C7, pages 31-47, provides a summary of activities to reduce concrete pavement noise by increasing longitudinal smoothness and providing the right kind of texture. The effort in Europe is somewhat different than in the U.S. (which has concentrated largely on transversely tined textures) due to the European focus on exposed aggregate surfaces and longitudinal textures.

## 4 SUMMARY OF ISSUES

The discussion of surface textures and the noise produced from the tire moving over them can be addressed as specific issues. Summaries of these issue papers are presented in this chapter.

### Issue: General Pavement Surface Type Questions

Pavement texture is needed to reduce the number and severity of wet weather accidents as defined in the *1976 AASHTO Guideline for Skid Resistant Pavement Design*. Each State should have developed a skid accident reduction program to determine when a surface texture will not aid in reducing wet weather accidents. Friction tests done as part of the skid accident reduction program should be performed with a ribbed and a smooth tire to obtain a measure of both the macrotexture and microtexture of the pavement surface. The speed gradient should also be determined and recorded with the friction number. **The use of the proposed International Friction Index would greatly reduce the cost of network level friction testing and also provide more meaningful results.** There is no current standard method for measuring tire / pavement noise; however, a prototype procedure has been developed as a byproduct of Wisconsin research.

### Issue: Safety of PCC and AC Surface Textures

The characteristics that relate to safe pavements (of any material) is adequate microtexture for stopping at all speeds and adequate macrotexture for surface drainage to prevent hydroplaning at high speeds on wet pavement so the tire remains in contact with the microtexture. Each material type and each respective surface texture has advantages and disadvantages when considering safety. Different conditions may suggest the use of a specific material and/or texture to meet design needs. However, safe pavement textures can be provided with either PCC or AC surfaces. In many cases, one of the major reasons dense graded AC pavements are quieter is that they have significantly less macrotexture than transversely tined PCC pavements. In addition to the specified design requirements, good friction and surface characteristics are directly related to good construction practices with high-quality materials. The adverse impact on safety and driving comfort of splash and spray from different pavement textures during rain is also a motorist concern.

### Issue: Tire / Pavement Noise on PCC and AC Pavements

A material type selection should not be made based solely on noise considerations from the tire / pavement interaction. Both FHWA and AASHTO currently recommend that safety not be compromised to obtain a slight, usually short-term, initial reduction in noise levels. Properly constructed PCC pavement, with a transversely tined or longitudinally tined surface, matches the performance of dense-graded asphalt considering both safety and noise factors. Available research data indicate it is the construction process, not an inherent material property difference between AC and PCC pavements, that currently results in slightly lower initial noise levels for AC pavements. Exposed aggregate surface treatments and Spanish longitudinal broom texture surfaces also provide good noise and safety related performance.

### Issue: Longitudinal and Transverse Tining

Both of these textures are acceptable from noise and safety requirements when properly constructed with durable aggregates. The mix design for a longitudinally tined PCC pavement should contain at least 25 percent siliceous sand and high-quality coarse aggregate. The texturing recommendations are the same as for transverse tining except a uniform spacing of 20 mm is recommended due to handling concerns by drivers of vehicles with smaller tires. The tire manufacturers reported that this factor is routinely considered during the design of current tire tread patterns. The transverse tines should be variably spaced between 10 and 40 mm (with no more than 50 percent of the spacing exceeding 25 mm), 3 mm wide, and 3 to 6 mm deep (resulting in an average texture depth of 0.8 mm with no individual test less than 0.5 mm as measured by the sand patch test). The random transverse tine spacing particularly will reduce the tire / pavement noise to an acceptable limit while providing a safe surface in wet weather due to good friction characteristics and reduced splash and spray.

### Issue: Premium Surface Treatments

There are several surface textures for new construction and for existing pavements that have been developed and used extensively or experimentally in the United States and Europe. These textures include: AC or PCC open graded, PCC exposed aggregate, diamond grooving, diamond or modified carbide grinding and shotblasting, PCC two-layer construction, and PCC chip sprinkling. PCC exposed aggregate may be the best new construction technique for noise reduction and safety. It may not, however, be the most cost-effective approach. Diamond or carbide grinding may not provide a long-term increase in friction when the large aggregate in the existing pavement is susceptible to polishing. Two-layer construction may be a cost-effective option when high-quality materials are not available in the immediate area.

## 5 FINDINGS AND RECOMMENDATIONS

Due to the almost unlimited combinations of climate; traffic; design, construction, and maintenance practices; materials cost and quality; and contractor experience and availability, the provision of a safe, durable, low-noise pavement surface is extremely complex. This paper is an attempt to summarize the current state-of-the-art and state-of-the-practice to help highway agencies select alternate material types and textures suited for their particular local conditions.
The efforts of the technical working group have helped reach a general consensus on procedures to consistently produce safe, durable, and low-noise concrete surfaces. The additional Wisconsin research underway will help refine the recommendations presented here and verify that the recommended procedures will obtain the desired results. The assistance of the technical working group members in addressing these issues and reviewing the proposed work plan and draft final report was greatly appreciated.

1. **Basis for Surface Texture Selection —** Well designed and constructed Portland Cement Concrete (PCC) pavements can provide safe, durable surfaces with low-noise characteristics. The selection of the surface texture to be provided at specific locations in a State should be based on existing conditions at that site, such as climate, amount of traffic including vehicle type distribution, speed limit, percent grade, conflicting movements (intersections or frequent side approaches), materials quality and cost, and the presence of noise-sensitive receptors. **The primary purpose of the surface texture is to help reduce the number and severity of wet weather accidents.**

   Where the State has data to show that a specific texturing method results in similar wet weather accident rates and/or has similar friction characteristics [when tested with an ASTM skid trailer (Method E 274), preferably with a blank tire (E 524)] to another texturing method or to alternate materials used, the State's proposed method should be allowed. **The State's pavement management and highway safety management systems should be**

**organized to develop these comparisons periodically.** Due to widely varying conditions at individual project locations, it is unlikely that one surface texturing method will always be the best choice in any given State.

2. **Safety Considerations** — The pavement surface on high-speed (80 km/h or greater) facilities must have sufficient microtexture (usually provided by siliceous sand) and macrotexture [provided by transverse or longitudinal tining (or plastic brushing–Spanish technique) preceded by a longitudinal artificial carpet or burlap drag; or an exposed aggregate surface treatment] to provide good friction characteristics during wet weather conditions. Current research and past experience have shown that longitudinal texturing with only an artificial carpet or burlap drag will generally <u>not</u> provide a safe, durable surface on high-speed facilities. They will usually provide adequate friction on roadways with speeds less than 80 km/h. **Both FHWA guidelines and the 1993 AASHTO Guide on the Evaluation and Abatement of Traffic Noise recommend that the designer should never jeopardize safety to obtain noise reduction.** Longitudinal tining or grooving should follow the *1976 AASHTO Guidelines for Skid Resistant Pavement Design* (1976 AASHTO Guide) due to the concerns expressed by drivers of vehicles with smaller tires.

   The total highway fatalities in the United States have increased from 39,235 in 1992 to 41,798 in 1995, reversing a long downward trend. In addition, 3,386,000 people were injured and 4,409,000 motor vehicle crashes involved property damage only. The increasing number of highway fatalities, plus the significant increases in the legal speed limits in many States as a result of the repeal of the national maximum speed limit by section 205(d) of the National Highway System Designation Act of 1995, reemphasize the need for providing safe, durable pavement surfaces.

3. **Need for Quality Mix Designs on Heavily Traveled, High-Speed Highways** — Adequate microtexture is <u>usually</u> most economically provided by specifying a minimum siliceous sand content of 25 to 40 percent of the fine aggregate portion of the mix. *FHWA Technical Advisory T 5080.17, Portland Cement Concrete Mix Design and Field Control*, dated July 14, 1994, reemphasizes good mix design practices. Fine aggregates usually containing a minimum of 25 percent siliceous sand; durable, nonpolishing coarse aggregates; a low water-cement ratio; an adequate air content; an adequate cement factor; and good curing practices are all necessary if a high-quality, durable concrete is to be provided.

   Where cost effective and high-quality aggregates are not readily available, consideration should be given to two-layer construction, wet on wet, with a higher quality mix in the thinner (Michigan DOT recommends a minimum thickness of 70 mm based on recent construction experience) surface layer. This may provide a more durable, yet economical concrete pavement.

4. **General PCC Surface Texture Considerations** — Transverse tining, preceded by a longitudinal artificial carpet or burlap drag, remains the most desirable PCC surface texture method for many high-speed (80 km/h or greater) locations. With quality design and construction, it has been shown that pavements with excellent friction characteristics and low-noise levels can consistently be provided. In particular, research demonstrates that transversely tined concrete pavements with low-noise characteristics and minimal splash and spray can be constructed.

   With high-quality mix design and construction practices, longitudinal tining or brushing and the exposed aggregate surface treatments will also provide sufficient macrotexture to prevent hydroplaning and reduce the number and severity of wet weather accidents on high-speed highways.

   **Transverse tining**—<u>When used, random transverse tine spacing (minimum spacing of 10 mm and a maximum spacing of 40 mm with no more than 50 percent of the spaces exceeding 25 mm) should be specified pending the results of further research</u>. The actual tine width should be 3 mm (+/- 0.5 mm), and the tined depth should be a minimum of 3 mm and a maximum of 6 mm (provided minimum dislodging of the aggregate particles results). Narrow (less than 4 mm width), deep grooves are considered better than wider, shallow grooves for minimizing noise. The average texture depth as measured by the sand patch test (ASTM E 965) should be 0.8 mm with a minimum of 0.5 mm for individual tests. Measurements of **random** spacings at two locations in Wisconsin that generate low-noise levels and no tire / pavement whine are as follows:

   32/19/22/25/35/22/22/22/22/25/35/13/38 mm
   16/25/22/16/32/19/25/25/25/25/19/22/25/22/10/25/25/25/32/38/22/25/22/25 mm

Wisconsin researchers have now developed a noise measuring system in a vehicle and an analysis method that will identify pavement textures that generate objectionable tonal qualities. The revised noise evaluation procedure was developed when previous research reports and the current study revealed that the subjective noise ratings given by persons in test vehicles on transversely tined and certain other types of textured pavements did not correspond with the objective total noise measurements taken 7.5 m from the pavement edge. Noise measurements were taken inside of vehicles with instruments using a Fast Fourier Transform (FFT) analysis mode to observe narrow band frequencies. It was discovered that there are peak sound pressure levels up to 15 dB(A) around 1,000 Hertz that cause a pure tone that is irritating to the human ear (either a higher frequency tire / pavement whine or, in fewer cases, a lower pitched rumble). The third octave band analysis was not detecting these frequency peaks because averaging of the total sound masked them. The tones were discovered on most uniformly spaced transverse tining. **This is a major discovery because surface textures creating these tonal characteristics can be identified so that they can be avoided on future projects.**

**Longitudinal Tining**—Where longitudinal tining is desired (particularly in noise-sensitive areas or drier and non-freezing climates), it is recommended that the uniform tine spacing be 20 mm, actual tine width 3 mm (+/- 0.5 mm), and the individual tined depth be 3 to 6 mm (with an average surface texture depth of 0.8 mm and a minimum of 0.5 mm for individual tests as measured by the sand patch test ASTM-E 965). Wider longitudinal grooves are particularly objectionable to drivers of vehicles with small tires and must be avoided.

Preliminary information indicates that longitudinal tining at 20 mm spacing, preceded by a burlap or artificial turf drag, will provide a safe, durable pavement <u>if</u> a high-quality surface mixture with adequate microtexture is used that includes a minimum of 25 percent siliceous sand. CALTRANS specifies a minimum siliceous sand content of 30 percent of the fine aggregate portion <u>and</u> a minimum friction coefficient of 0.30 per its standard test procedure.

When considering the use of longitudinal texturing, the disadvantages of slightly slower surface drainage and more splash and spray compared to transverse tining should be considered especially in wetter climates subject to freezing conditions. Where very high speeds are expected (130 km/h or greater), British research indicates that longitudinal textures may not provide satisfactory friction characteristics. The New South Wales, Australia, *Concrete Pavement Manual* also states that longitudinal grooving treatment is unsatisfactory for both stopping distance and for rotational stability of a braked vehicle at high speeds .

**Longitudinal plastic brushing**—Spain has reported the successful use of a combined texture consisting of a longitudinal burlap drag followed by a plastic brush to provide high-friction characteristics while minimizing tire / pavement noise. A minimum of 30 percent siliceous sand is required to assure satisfactory microtexture. An average texture depth of 0.7 to 1.0 mm is required. Skid resistance is reported similar to porous asphalt with an average noise level of 0 to 2 dB(A) or higher (this noise level difference is not discernable by the human ear). Two PIARC study locations in Spain had .29 and .21 Friction Numbers with mean texture depths averaging 1.1 mm and 0.8 mm, respectively, when tested in 1992 at 90 to 95 km/h (55 mph) by an ASTM skid trailer with a blank tire. The $SN_{40}$ ribbed tired friction numbers were .53 and .41 and the $SN_{40}$ blank tire friction numbers were .48 and .27 respectively. The wet weather accident rate for this texture compared to other textures or surface types is not currently available.

**Exposed Aggregate Surface**—The exposed aggregate surface treatment technique is normally constructed on a pavement composed of two layers (wet on wet): top layer 40 to 70 mm thick, 30 percent siliceous sand 0 to 1 mm and 70 percent high-quality chips 4 to 8 mm (Los Angeles abrasion less than 19, polished stone value greater than 50); bottom layer maximum aggregate size 32 mm with lower quality yet durable aggregates. A high-quality concrete, with a maximum water-cement ratio of 0.38, minimum 450 kg/m$^3$ cement content, a plasticizer, and an air entrainment agent, is used in the top layer to ensure durability and to keep the modulus of elasticity as high and shrinkage as low as the bottom layer. Recommended texture depth is 0.9 mm as measured by the sand patch test ASTM E 965 (less depth is reported to result in higher noise). If 60 or more chips per 2,500 mm$^2$ are exposed, the noise will be low. Overfinishing of the surface must be avoided, and special vibrators must be used for the top layer. Advantages include noise similar to porous asphalt, excellent high-speed skidding resistance, and low splash and spray.

**Other options that have been used include:**

- Sweden has reduced the water-cement ratio and added microsilica to improve wear resistance against studded tires.
- The United Kingdom used 6 to 10 mm chips for a 1.4 mm average texture depth and has obtained excellent high-speed (130 km/h) skidding performance.
- Belgium has constructed CRCP in one layer with an exposed aggregate surface by reducing the maximum aggregate size to 20 mm and increasing the amount of 4 to 7 mm chips.

5. **Profile Considerations —** Some deep transverse tining has resulted in dislodging the aggregate particles with a resulting decrease in pavement ride quality and an increase in objectionable tire / pavement noise. However, a 1974 Belgian study concluded that randomly spaced (15 to 30 mm), deeper transverse tining (5 to 7 mm depth) did not affect the evenness (roughness) of the pavement surface and thus did not reduce the riding quality as compared to untined roads.*(13)*

   The International Roughness Index (IRI) is considered the best current indicator of pavement surface smoothness. European research indicates that the pavement smoothness also affects the noise level and an additional or an improved longitudinal smoother is being used to reduce total PCC tire / pavement noise to a level similar to that of a dense graded asphalt.

6. **Alternative Surface Treatments to Improve Friction Properties of Existing Portland Cement Concrete Surfaces —** There are many tradeoffs necessary in design, construction, materials quality, and maintenance procedures primarily due to the limited funding available. Therefore, it may be necessary to restore friction properties on sections of roadways with a high ratio of wet weather accidents or possibly on pavements having undesirable noise characteristics.

   Possible alternatives to restore a skid resistant surface on Portland Cement Concrete (PCCP) pavements include:

   - longitudinal or transverse grooving with diamond saws
   - retexturing with diamond or modified carbide grinding or shotblasting
   - thin surface laminates or bonded concrete overlays
   - surface treatments like epoxy resin/calcined bauxite, Ralumac, or Novachip
   - asphalt concrete (AC) overlays (dense- or open-graded)

   It is normally more cost effective to retexture the existing concrete surface than provide a thin surface treatment or overlay unless polishing aggregates are involved.

7. **Research Needs —** A review of the State-of-the-Practice and the State-of-the-Art revealed the following areas where additional research is needed:

   - Available information supports only a general correlation between friction numbers and wet weather accident rates. Additional analyses over consecutive 3- to 5-year periods is needed to determine (1) the wet weather accident rates of different textures and pavement types and (2) the change in friction numbers and accident rates over time for the different textures and pavement types.

   - Much current information is based on initial values of noise for different surface textures, which can change significantly both short- and long-term. The NCHRP Synthesis of Highway Practice Topic 26-05, "Relationship of Pavement Surface Texture and Highway Traffic Noise," study underway will address the change in noise levels and in friction over time. Better information is needed on the change in noise levels for various surface textures for their full service lives so appropriate tradeoffs between noise and safety considerations can be made.

   - *These analyses are needed to assure that safe, durable pavement surfaces are being provided. Slight [up to 3 dB(A)] noise increases, which are not discernable to the human ear, should not override the need to provide sufficient macrotexture to prevent hydroplaning on high-speed (80 km/h or greater) facilities. Textures known to cause pure tone frequencies (narrow band analysis) should be avoided.*

- **The appropriate ASTM Committee should address the desirability of using the blank tire (ASTM E 524) for skid inventory purposes due to its higher correlation with wet weather accident rates.** Also, the recently developed PIARC system for skid testing with a blank tire only and a concurrent texture measurement to develop an International Friction Index, should be considered for adoption. This method also allows an evaluation of the speed gradient and allows International comparisons between the results of different skid testing equipment. **Use of the PIARC developed system will also greatly reduce the cost of skid inventory testing.**

- Additional research appears to be necessary to define the most desirable random transverse tine spacing and repeat pattern to optimize safety and noise characteristics. Also, there are differing opinions regarding the effect of depth of transverse tining on noise generation. It is recommended that future research involving texture depth measurements be analyzed to evaluate the interaction of groove width, depth, and spacing on the generation of objectionable tonal noises. The literature search suggests that the groove width and spacing are more critical than the depth of tining. This conclusion is disputed by some researchers, and this issue needs to be resolved.

- Automated texture measuring devices need to record both longitudinal and transverse texture to obtain average texture depths similar to the sand patch test to help evaluate the surface drainage quality of the various textures. Simultaneous recording of longitudinal grade and transverse cross slope would help to further characterize the surface drainage conditions. Further development of the outflow meter (including specifications to ensure uniformity of manufacture) should be done to help determine the quality of surface drainage.

- PCC construction techniques need to be revised to eliminate short wavelength roughness, which contributes to increased tire / pavement noise. A more accurate method to determine smoothness is needed for construction control. The Final Report for NCHRP Project 1-31, "Smoothness Specifications for Pavements," is now available. NCHRP Project 10-47 will provide additional guidelines for specifying equipment and procedures to measure the initial ride quality.

- The effect of surface texture on drainage (such as friction, splash and spray, and any special winter maintenance considerations) needs to be better defined so appropriate trade-offs can be made. NCHRP Project 1-29, "Improved Surface Drainage for Highway Pavements," will provide improved guidance. However, specific information comparing the effects of longitudinal and transverse textures on surface drainage characteristics and related safety effects is needed.

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