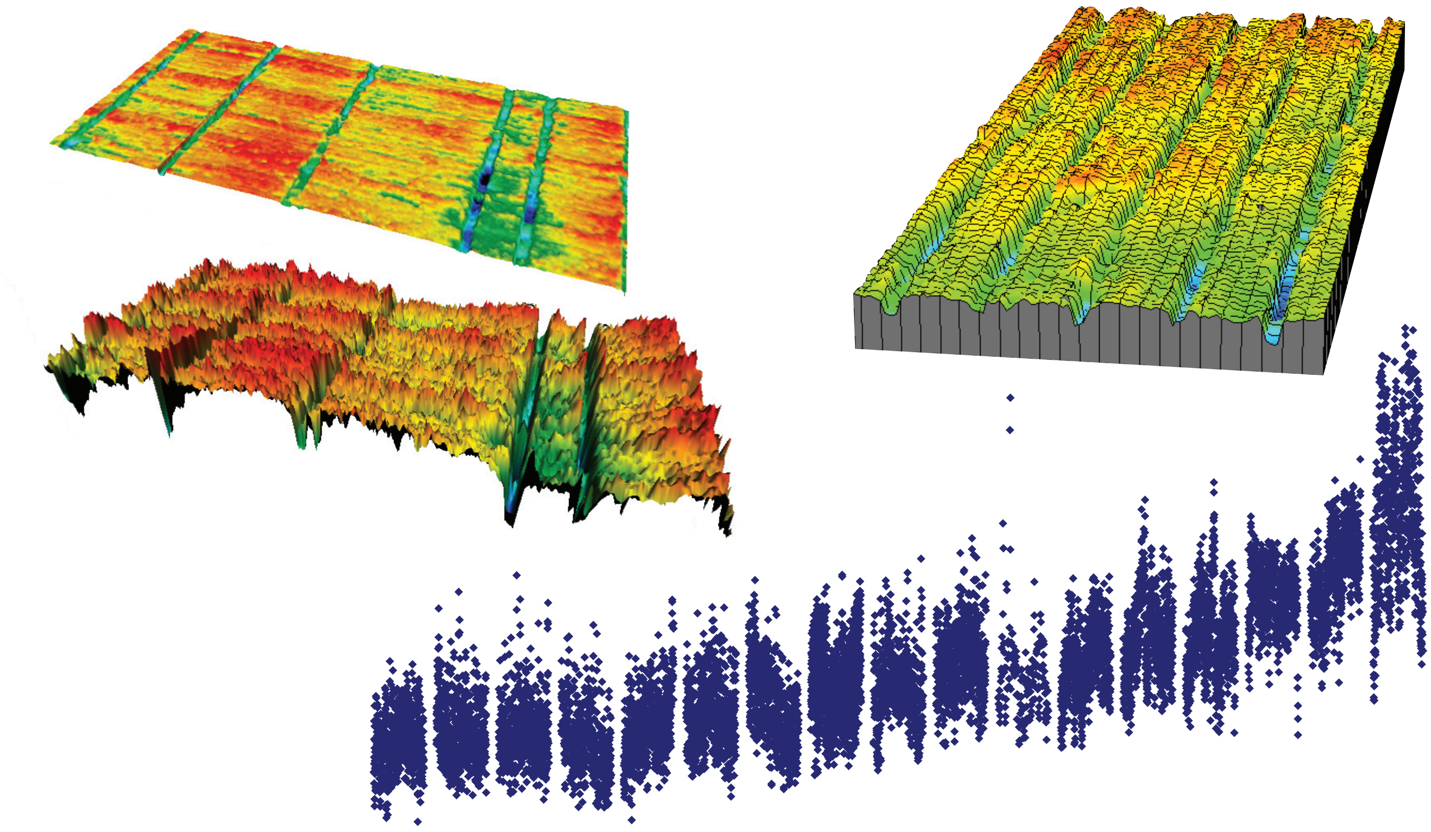
National Concrete Pavement Technology Center

Evaluation of U.S. and European Concrete Pavement Noise Reduction Methods

July 2006

Sponsored by
Federal Highway Administration
Cooperative Agreement DTFH61-01-X-00042 (Project 15)

Part 1, Task 2, of the ISU-FHWA-ACPA Concrete Pavement Surface Characteristics Project



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Center for Transportation Research and Education

Iowa State University

National Concrete Pavement Technology Center
2711 South Loop Drive, Suite 4700
Ames, IA 50010

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Part 1, Task 2, of the ISU-FHWA
Concrete Pavement Surface Characteristics Project

Principal Investigator
E. Thomas Cackler
Director, National Concrete Pavement Technology Center, Iowa State University

Co-Principal Investigators
Theodore Ferragut
President, TDC Partners, Ltd.

Dale S. Harrington
Principal Senior Engineer, Snyder & Associates

Principal Project Engineer
Robert Otto Rasmussen, Ph.D.
Vice President and Chief Engineer, the Transtec Group, Inc.

Project Manager
Paul Wiegand
Research Engineer, National Concrete Pavement Technology Center, Iowa State University

Research Associates
Robert Bernhard, Ph.D., Institute for Safe, Quiet and Durable Highways, Purdue University
James Cable, Ph.D., Iowa State University
George K. Chang, Ph.D., the Transtec Group, Inc.
Gary Fick, Trinity Construction Management Services
Steven Karamihas, Ph.D., Transportation Research Institute, University of Michigan
Eric Mun, the Transtec Group, Inc.
Robert Prisby, American Concrete Pavement Association Pennsylvania Chapter
Yadhira A. Resendez, the Transtec Group, Inc.
Ulf Sandberg, Sc.D., Swedish National Road and Transport Research Institute (VTI)

Federal Highway Administration (FHWA)
Mark Swanlund, Senior Pavement Design Engineer, Office of Pavement Technology

National Concrete Pavement Technology Center
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010
www.cptechcenter.org
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About the National Concrete Pavement Technology Center

The mission of the National Concrete Pavement Technology Center is to unite key transportation stakeholders around the central goal of advancing concrete pavement technology through research, tech transfer, and technology implementation.

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1. Introduction

1.1. PROJECT OVERVIEW

Highway noise is one of the most pressing of the surface characteristics issues facing the concrete paving industry. This is particularly true in urban areas, where not only is there a higher population density near major thoroughfares, but also a greater volume of commuter traffic (Sandberg and Ejsmont 2002; van Keulen 2004).

To help address this issue, the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University (ISU), Federal Highway Administration (FHWA), American Concrete Pavement Association (ACPA), and other organizations have partnered to conduct a multi-part, seven-year Concrete Pavement Surface Characteristics Project.

This document contains the results of Part 1, Task 2, of the ISU-FHWA project, addressing the noise issue by evaluating conventional and innovative concrete pavement noise reduction methods. The first objective of this task was to determine what if any concrete surface textures currently constructed in the United States or Europe were considered quiet, had long-term friction characteristics, could be consistently built, and were cost effective. Any specifications of such concrete textures would be included in this report. The second objective was to determine whether any promising new concrete pavement surfaces to control tire-pavement noise and friction were in the development stage and, if so, what further research was necessary. The final objective was to identify measurement techniques used in the evaluation.

The Part 1, Task 2, evaluation reported herein included

- examination of conventional concrete pavement noise reduction methods used in the United States;
- identification of promising new concrete pavement surfaces to control tire-pavement noise and friction in Europe; and
- initial consistent field measurements of tire-pavement noise and friction with respect to texture.

Conventional U.S. Concrete Pavement Noise Reduction Methods

The project team performed a review and evaluation of current concrete pavement noise reduction methods and noise reduction research (Section 2 of this document). Previously, numerous important individual studies, including some in Europe, Colorado, California, and Wisconsin, have been conducted to evaluate highway noise in the context of specific projects. Many of these studies are summarized herein and also are reviewed in the ACPA engineering bulletin *Pavement Surface Characteristics: A Synthesis and Guide* (ACPA 2006).

The project team evaluated the referenced studies in 2004/2005 and concluded that although artificial turf drag, burlap drag, and longitudinal tining appeared to offer the best U.S. conventional plastic-placed concrete textures, the methods of measurement and research protocols used for each of the studies varied significantly and that, as such, any comparisions between them or conclusions drawn collectively from them could not be made with any degree of statistical confidence. Regarding hardened concrete texturing, it has been known for some time that diamond grinding can provide smoothness, acoustic durability, and skid resistance for years. (It should be noted that long-term surface characteristics measurements need to be completed to help ensure these textures have low noise and adequate friction for specified periods of time.)

Rather than compare unlike measurements from a variety of past studies, the research team and project sponsors initiated field evaluations to provide a controlled evaluation of texture versus desired surface characteristics. In order to accurately evaluate and compare current methods, the project team determined that concrete pavements with different types of employed textures would need to be built, measured and monitored. The ongoing field evaluations make up Parts 2 and 3 of this research project.

Promising New European Concrete Pavement Surfaces to Control Tire-Pavement Noise

The project team also identified and evaluated innovative surface that have the potential to reduce noise by an order of magnitude or more without degrading other surface characteristics (friction, smoothness, drainage, etc.) of the pavement (see Section 3).

Potential innovative solutions include stamping, brushing, and other new texturing techniques; exposed aggregate concrete pavements; pervious concrete pavements; sprinkle treatment; and shot peening.

Two of these promising innovative concrete pavement solutions, exposed aggregate concrete pavements and pervious concrete pavements, have been identified as potential candidates for fast-track advancement. These technologies require further study and detailed cost-effectiveness evaluation before becoming part of common practice throughout the United States.

To provide the latest information available, the project team set specifications for U.S. application of the exposed aggregate concrete pavements commonly used in Europe to control tire-pavement noise (see Appendix B). The project team also developed a research plan to evaluate and recommend pervious surface course designs and construction procedures for additional applications than currently practiced (see Appendix C).

Field Measurements of Tire-Pavement Noise with Respect to Texture

In January 2005, the ACPA joined with the CP Tech Center and the FHWA to help organize and implement a comprehensive field experiment plan to evaluate and compare current surface characteristics practices. The project team initially thought that a sufficient understanding of the capabilities of conventional methods would be covered through the evaluation of current European and U.S. methods. However, at the November 2004 workshop it was concluded that there was an urgent and critical need to provide short-term solutions using existing technologies. It was determined that in order to accomplish this, immediate field experiments were needed to determine the conventional surface textures that were the quietest and that could be repeatedly and consistently built. Thus, the field evaluation portion of the project was established.

The objective of the initial field evaluation is to measure and analyze conventional texturing variations and grinding techniques and their respective surface characteristics, particularly with respect to tire-pavement noise. This evaluation is ongoing at the time of this writing. Preliminary noise-texture measurement conclusions are included in Section 5.

1.2. CONTENTS OF THIS DOCUMENT

This document contains the following sections:

- Section 1. Introduction
- Section 2. Conventional U.S. and European Concrete Pavement Noise Reduction Methods
- Section 3. Promising New Concrete Pavement Surfaces to Control Tire-Pavement Noise
- Section 4. Field Measurements of Tire-Pavement Noise with Respect to Texture
- Section 5. Conclusions
- Appendix A. Basics of Texture, Noise, Friction, and Smoothness
- Appendix B. Exposed Aggregate Concrete Pavement Specifications
- Appendix C. Research Plan for Pervious Concrete Pavements

This evaluation concludes that

- careful construction practices in the United States for artificial turf and burlap drag, longitudinal tining, and diamond grinding can be used to initially control noise (99/100–104/105 dBA) and provide adequate initial friction (long-term surface characteristics measurements need to be completed to help ensure these textures have low noise and adequate friction for specified periods of time);
- the noisest pavements (>104/105 dBA) should be rehabilitated immediately, with no new noisy pavements constructed;
- to achieve the quietest concrete pavements (<99/100 dBA), innovative solutions such as exposed aggregate and pervious concrete, need to be advanced; and
- more study is necessary to understand the change of noise and texture characteristics over time and to increase consistency.

1.3. BACKGROUND ON THE NOISE ISSUE

One of the most pressing issues facing highway owners is perceived noise by travelers and abutters. While the noise produced from tire-pavement interaction is just one of several noise sources for almost all roads, it becomes the primary source of traffic noise for vehicular speeds over 55 km/h (35 mph) (ACPA 2000). In the United States, nearly 70% of the noise on high-speed facilities dominated by automobiles is generated at the tire-pavement interface (as track traffic volumes increase, truck noise becomes more predominant).

To mitigate the noise, at least for the highway abutters, engineers normally specify noise barriers (Roberts, Voigt, and Ayers 2004). However, noise barriers are expensive, and it has been shown that they are ineffective as a noise-dampening solution (van Keulen 2004; Hansen et al 2004).

Demands for quieter roadways have sometimes contributed to the decreased use of concrete pavement as a construction option and in some cases even resulted in the overlay of recently constructed concrete pavements. In the Phoenix metropolitan area, for example, concrete pavements with an aggressive transverse texture make up nearly all of the freeway system. Because of noise complaints, these pavements are now being overlaid with an open-graded asphalt-rubber wearing course.

Engineers in the European Union have developed alternative pavement types and surfaces that reduce the noise generated at the tire-pavement interface (European Union 2002). Many European nations now place thin, asphalt-based wearing courses over their concrete pavements immediately after construction. Success has been demonstrated with some concrete surfacing solutions as well. Specifically, thin, open-graded (pervious) concrete wearing surfaces as well as exposed aggregate surfaces have been shown to reduce noise when compared with other pavement types. Textures including turf and burlap drag and diamond grinding have also been used successfully to reduce noise.

Although some quieter pavements can be initially more costly than conventional pavements, their application can possibly reduce or even eliminate the need for noise barriers (Ingram et al. 2004). Pavements containing materials with desirable absorption characteristics also have the ability to reduce roadside sound, since the sound generated by the passing vehicle will not reflect off the pavement as easily. Selection of an ideal pavement for a given location is a complex problem, often a function of several competing variables, such as safety, cost, climate, speed, traffic levels, the pavement’s location with respect to heavily populated areas, and durability.

In the United States, FHWA regulations currently dictate the noise mitigation efforts that must be used for new or expanded highway facilities to address noise impacts to highway abutters. To date, these regulations have resulted in questions about whether noise walls are necessary and, if so, what their design should be. The pavement itself is now also expected to help in noise reduction. This will require concrete pavement engineers to take responsibility for finding innovative materials and optimizing pavement textures.

One confounding obstacle to improving texturing methods and innovative surfaces is that previous research is not conclusive about the relationship between texture direction, depth, width, and noise generation, either initially or over time (Wayson 1998). New techniques to measure noise and texture are now coming online and may assist in determining the relationship between these two properties. Modeling and laboratory evaluations are also relatively new in this field, leaving empirical techniques as the primary source of data.

2. Conventional U.S. Concrete Pavement Noise Reduction Methods

This section contains information on conventional concrete pavement surface options for controlling tire-pavement noise. These fall into the following categories:

- Conventional texturing (performed while concrete is still a plastic state)
    - Drag textures (including artificial turf and burlap drag)
    - Tined textures (including transverse and longitudinal)
- Diamond grinding (performed on hardened concrete pavement)

2.1. CONVENTIONAL TEXTURING

Drag Textures

Prior to the mid-1960s, pavement finishing was limited to shallow texturing techniques, such as brooming or dragging (Hoerner and Smith 2002). Broomed surface textures are created by dragging a handheld or mechanical broom along the surface of the pavement, creating a ridged surface. This texture typically consists of 1.5- to 3-mm-deep (0.06 to 0.12 in.) grooves, either longitudinal or transverse to the centerline of the roadway (ACPA 2004).

Artificial turf drag surfaces are similarly created by dragging an inverted section of artificial turf along the surface of the pavement. Today, this technique often employs a device that controls the time and rate of texturing, most commonly a construction bridge that spans the pavement. Grooves of 1.5 to 3 mm (0.06 to 0.12 in.) in depth are typically created (ACPA 2004).

Burlap drag (also known as Hessian drag) texturing is created by dragging moistened, coarse burlap across the surface of the pavement, typically creating grooves with depths between 1.5 and 3 mm (0.06 and 0.12 in.) (ACPA 2004).

Artificial turf drag texturing is shown in Figures 2.1 and 2.2. Burlap drag texturing is shown in Figures 2.3 and 2.4.

Figure 2.1. Artificial turf drag method

Figure 2.2. Artificial turf drag texture

Figure 2.3. Burlap drag method

Figure 2.4. Burlap drag texture

Although the use of these shallower texturing techniques commonly leads to quieter pavements, concerns about adequate skid resistance have also been reported, particularly for high-speed facilities (Hoerner and Smith 2002). Studies have shown that dragged textures are sufficient for roadways with speeds less than 72 km/h (45 mph) (ACPA 2000). Furthermore, recent pavement evaluations in Minnesota have concluded that the use of drag texturing results in comparable noise levels and surface friction to conventional hot-mix asphalt (HMA) pavements (ACPA 2000). The required texture depth specification in Minnesota is reported to be 1.0 mm (0.04 in.).

In Germany, the majority of concrete highway systems are finished using a burlap drag texture (Sulten 2004; Larson, Vanikar, and Forster 1993). Tining is not used in their pavements due to concerns about pavement noise. The burlap drag finish provides adequate friction and minimizes air pumping; however, the frictional characteristics of the pavements often decrease due to pavement wearing. Although the use of larger sand particles may increase the texture life by up to six years, the larger sand may also reduce the concrete's workability (Buys 2004). German recommendations for burlap drag include the following (Sulten 2004):

- Minimum weight of 300 g/m^2 (0.55 lb./sq. yd.)
- Minimum concrete contact length of 2 m (6.5 ft.)
- Fringe length (at trailing edge) of approx 3 cm (1.2 in.)
- Slightly moistened burlap before first usage
- Burlap replaced or washed at least once each day

In summary, drag texturing techniques could provide a less costly and often quieter pavement than many alternatives. However, measures should be taken to ensure adequate friction, both initially and during the service life. This appears to be best done by selecting materials and mixes with improved wear resistance.

Tined Textures

Transverse Tining

Transverse tining is one of the most commonly used texturing methods on higher speed concrete pavements. It is considered an inexpensive method for durable, high-friction surfaces on new concrete pavements (Hoerner and Smith 2002). Favorable friction qualities of transverse tining are particularly pronounced in wet weather conditions, as deep macrotexture is capable of reducing the water film thickness and thus the potential for hydroplaning. Depending on the properties of the concrete mixture, transverse tining can provide beneficial friction qualities over the life of the pavement.

Transverse tining has also been known to exhibit undesirable noise emissions due to the interaction of the pavement and vehicle tires. Noise emissions from transverse tined textures depend on tine spacing, depth, and width. A study conducted by the Wisconsin Department of Transportation in 2000 concluded that wider and deeper transverse tine textures often produce greater noise (Kuemmel et al. 2000).

Transversely tined textures are created using a tining device, commonly a metal rake that is either controlled by hand or attached to a mechanical device. Tines are moved across the width of the pavement. Individual tines can be either uniformly or randomly spaced. Tine width is typically 3 mm (0.125 in.) while the depth is typically 3 mm (0.125 in.), but depth reportedly varies between 1.5 and 6 mm (0.0625 and 0.25 in.) (ACPA 2004).

Uniform transverse tine spacings typically range from 12.5 to 25 mm (0.5 to 1 in.). See Figure 2.5. “Wheel whine” is often associated with uniformly spaced tines. While the dBA level of a tined surface may not necessarily be higher than other texturing methods, the tonal nature of the whine makes this pavement texture objectionable to many.

To help mitigate the tonal qualities, random tining has been recommended. See Figure 2.6. A broad range of random tine spacings, between 10 to 76 mm (0.4 to 3 in.) has been reported to reduce noise emissions (Hibbs and Larson 1996; Wayson 1998). In situations where concrete finishing conditions are unfavorable (e.g., objectionable weather conditions and lack of equipment control), random spacings of 10 to 51 mm (0.4 to 2 in.) are recommended. The FHWA has recommended two random tining patterns, averaging 13 mm and 26 mm (0.5 in. and 1.0 in.), respectively (FHWA 2005). The shorter spacings have been recommended to mitigate the high noise levels reported by some states that have tried or adopted random spacings.

Figure 2.5. Transverse tining—uniformly spaced

Figure 2.6. Transverse tining—randomly spaced

Skewing of transverse tining involves forming the grooves at an angle, rather than perpendicular to the centerline. This is a complementary method that has demonstrated benefits related to tire-pavement noise while providing the friction commonly associated with transverse tined pavements. Research has identified a skew with a recommended longitudinal-to-transverse ratio of 1:6 (Kuemmel et al. 2000).

In one study, comparisons were made between transverse tining and longitudinal diamond-ground pavement texturing (discussed later). Sample sections were constructed and evaluated for safety, noise, and other pavement characteristics (Burgé, Travis, and Rado 2001). The tined pavement was constructed using spring steel tines with a width of 3.1 mm (0.122 in.), based on research aimed to reduce tire-pavement noise or "wheel whine."

While this study concluded that randomly spaced tining minimized audible whine, overall sound levels were also noted to increase. Furthermore, when the Arizona DOT constructed a test section with the same random texture specified by the Wisconsin DOT, subsequent measurements revealed high tire-pavement noise. The difference is believed to be due to both texture depth and the presence of "positive texture" resulting from latent material being removed from the tine grooves and deposited on the pavement surface.

Longitudinal Tining

Longitudinally tined textures are constructed in a manner similar to that of transverse tining, except that the tining device is moved longitudinally along the direction of paving. Although longitudinal tining is not used as frequently as transverse, it has been used extensively in some states, including California. See Figure 2.7.

Figure 2.7. Longitudinal tining

Longitudinal tining is commonly reported to exhibit lower noise characteristics and is thus increasing in popularity (Hoerner and Smith 2002; ACPA 2004; ACPA 2002; Scofield 2003). Some cautiousness to change has stemmed from data that have shown longitudinally tined surfaces to have lower friction numbers when compared to transversely tined pavements, all else being equal (Hoerner and Smith 2002). One possible explanation of this may be the shape of the grooves with respect to the traction forces of the tire (compared to transverse tining). It should be noted, however, that longitudinal tining on horizontal curves has been shown to prevent vehicle skidding and improve safety (Transtec Group 2005). Furthermore, some DOTs have reported that if adequate cross-slope exists, the differences between the surface drainage on transverse and longitudinal tining are minimal.

In order for longitudinally tined textures to provide optimal noise reduction performance, some recommend the design of the texture as follows: uniform tine spacing of 19 mm (0.75 in.), tine width of 3 ±0.5 mm (0.125 ± 0.02 in.), and an individual tine depth of 3 mm (0.125 in.) (Hibbs and Larson 1996; FHWA 2005). Deeper tining reportedly exhibits more noise, regardless of the orientation of the texture (Kuemmel et al. 2000). However, variability in tining depth currently makes this type of conclusion difficult to substantiate.

Research has shown that the long-term effectiveness of longitudinally tined surfaces is impacted by the design of the pavement mix. Data have shown that longitudinally tined pavements should contain a minimum of 25% siliceous sand to improve the level and durability of the friction capacity (ACPA 2000). Regardless of the mixture design, the use of studded tires has been shown to diminish the texture of the longitudinal tining over time (Sommer 1994; Hoerner and Smith 2002).

A Wisconsin DOT study further concluded that among all of the concrete pavements evaluated, those with longitudinal tining provided “the lowest exterior noise while still providing adequate texture” (Kuemmel et al. 2000). When the texture is properly designed and constructed, longitudinally tined pavements can achieve friction characteristics and durability comparable to either transversely tined concrete pavements or dense-graded HMA pavements (Hibbs and Larson 1996).

2.2. DIAMOND GRINDING

Diamond grinding is a technique that removes a thin layer of hardened concrete pavement using closely spaced diamond saw blades. The diamond saw blades are stacked side-by-side and generally remove between 3 and 20 mm (0.12 and 0.79 in.) from the surface. The blades are gang-mounted on a cutting head and can generate 164 to 197 grooves/m (50 to 60 grooves/ft.) (ACPA 2004). This technique should not be confused with milling, which employs carbide teeth that “rip” into a pavement surface, leaving a very rough texture. See Figures 2.8 (Caltrans 2005) and 2.9 (Wiegand et al. 2005).

Figure 2.8. Diamond ground pavement

Figure 2.9. Texture after diamond grinding

Although diamond grinding has traditionally been used to rehabilitate existing pavements by restoring smoothness, it has also been found to reduce tire-pavement noise and restore pavement friction (Burgé, Travis, and Rado 2001; Sommer 1994; Donovan 2004; Roberts, Voigt, and Ayers 2004). This raises the possibility of using this technique as an initial texturing method for newly placed concrete pavements. The grinding procedure results in the development of macrotexture and, in some cases, exposure of increased microtexture. Furthermore, directional stability is more easily controlled, making this technique more appealing to drivers than longitudinal tining.

In one study conducted to compare transverse tining to longitudinal diamond-ground pavement texturing, test sections were constructed and evaluated for safety, noise, and other pavement characteristics (Burgé, Travis, and Rado 2001). Diamond grinding was used to remove a thin layer of the concrete surface. In some cases, thin fins of concrete were left behind and were subsequently broken off by a blade. Each grinding head consisted of 166 saw blades, 3.18-mm-thick (0.125 in.) separated by spacers with a thickness of 2.67 mm (0.105 in.).

It has been reported that the key variables of diamond grinding are cutting blades, cut depth, equipment horsepower, and the properties (e.g., hardness) of the aggregates used. In a study by Burgé, Travis, and Rado (2001), the grinding rate was approximately 0.6 lane-km (0.4 lane-mi.) per day; in addition, there was a specified minimum curing time of seven days necessary before grinding.

The study concluded that the longitudinal ground pavement was quieter than the transversely tined pavement by 2 to 5 dBA (measured on the side of the road). When noise measurements were conducted a year later, there was a negligible change in noise levels. When comparing different vehicle types, the ground surface led to a 5-dBA noise improvement for light trucks and automobiles, and a 2-dBA improvement for medium and heavy trucks. The lower noise reduction for larger vehicles is believed to be due to differences in the noise emission source; larger vehicles generate a greater percentage of noise from the engine and exhaust systems (as compared to tire-pavement noise emissions).

On State Route 202 in Arizona, the Arizona DOT evaluated four test sections constructed using varying diamond grinding textures (Scofield 2003). The original texture of the pavement was a uniform longitudinally tined texture with 19-mm (0.75-in.) tine spacings. Four sections of the pavement were ground with differently sized blade spacers and grinding depths:

- Section 1: Profile grind with 2.79-mm (0.110-in.) spacers
- Section 2: Profile grind with 2.79-mm (0.110-in.) spacers with jacks and a floating head
- Section 3: Profile grind with 3.05-mm (0.120-in.) spacers
- Section 4: Profile grind with 3.05-mm (0.120-in.) spacers with jacks and a floating head

The use of jacks and a floating head relieved downward pressure and affected the depth, creating shallower cuts. Texture depth was not explicitly measured. This study initially concluded that Section 4 led to the greatest initial noise reduction compared to the other test sections, with a reduction in noise between 3 and 6 dBA.

However, measurements taken one year later demonstrated the opposite trend, with the narrower 2.79-mm (0.110-in.) spacers resulting in the quietest pavements. The Arizona study also concluded that grinding reduced the International Roughness Index (IRI) of the pavement by 58% and increased the frictional capacity by 27%. It was reported that these test sections produced the smoothest and quietest concrete pavements in Arizona.

The Kansas DOT conducted a similar study in 2004, also concluding that smaller blade spacings led to decreased noise levels (Transtec Group 2005). Since little characterization of the surface texture from either study is available, a more detailed analysis of the results from these studies remains to be done. Only when the texture geometry can be characterized along with the corresponding noise and other pavement surface characteristics will the optimum “whisper grind” technique be fully realized.

3. Promising New European Concrete Pavement Surfaces to Control Tire-Pavement Noise

The Concrete Pavement Surface Characteristics project team is identifying and evaluating innovative surface that have the potential to reduce noise by an order of magnitude or more, while also not degrading the other surface characteristics (smoothness, friction, drainage, etc.) of the pavement. Contractors and engineers have been offering insights and ideas on new approaches to texturing concrete pavements.

Potential innovative solutions include exposed aggregate concrete pavements; pervious concrete pavements; stamping, brushing, and other new texturing techniques; sprinkle treatment; and shot peening. These techniques are each discussed briefly in this section.

Two of these promising innovative concrete pavement solutions, exposed aggregate concrete pavements and pervious concrete pavements, have been identified as promising candidates for fast-track advancement and are described in more detail in this section. These technologies require further study or specification development before becoming part of practice.

As a result, the project team developed specifications for U.S. application of the exposed aggregate concrete pavements commonly used in Europe to control tire-pavement noise. The project team also developed a research plan to evaluate and recommend pervious surface course designs and construction procedures for additional applications than currently practiced. These documents are included in the Appendix B.

Appendix C includes a detailed research plan for advancing pervious concrete solutions. The specifications and research plan were developed in fulfillment of Part 1, Task 2b, of the ISU-FHWA-ACPA Concrete Pavement Surface Characteristics Project sponsored by the Federal Highway Administration.

3.1. SUMMARY OF POTENTIAL INNOVATIVE SOLUTIONS

Two-Lift Construction with an Exposed Aggregate Concrete Pavement Surface

Two-lift construction involves the placement of two wet-on-wet layers or bonding wet to dry layers of concrete, instead of the homogenous single layer commonly placed in concrete paving. The bottom layer is thick and consists of lower quality (lower durability or strength), locally available aggregate or recycled aggregate (such as recycled asphalt, concrete rubble, or local aggregate). The top layer is thin and consists of high-quality aggregate designed to provide better resistance to freeze-thaw damage, reduced noise, or improved friction.

Pervious Concrete Pavement

Pervious or porous concrete pavement is a special blend of portland cement, coarse aggregate, and water. Because of the minimum amount of sand, the void space is between 15% and 30%. Instead of allowing rainwater to run off the pavement, these voids allow rainwater to percolate through it without compromising the strength, durability, or integrity of the concrete structure itself. Pervious concrete is not a proprietary product; it is a “recipe” for concrete that can be made to order by any concrete batch plant.

Stamping, Brushing, and Other Texturing Techniques that May be Developed

Some believe that it is possible to develop an alternative texture to tining that can be placed in fresh concrete at approximately the same cost as conventional tining but that will have better surface characteristic properties than conventional tining. The FHWA is currently considering innovative work in this area.

Sprinkle Treatment

Sprinkle treatment is similar in concept to exposed aggregate techniques. Small, polish-resistant stone chips are distributed on the fresh concrete surface, and techniques are applied to partially embed the stones. Though this technique was used in the 1970s and 1980s in the United States, the equipment was rented from England and the process never caught on. It is believed that it could be used for skid and noise applications, now that functional issues have become more important. Note that for sprinkle treatments to be effective, innovative application equipment needs to be available.

Shot Peening (Shotblasting)

Shot peening is a procedure in which specialized equipment propels tiny steel shot onto the pavement surface. The shot impacts the surface and removes a thin layer of mortar and aggregate, which exposes coarse aggregate and creates an open porous surface texture that appears to increase skid numbers and reduce noise characteristics. Considerations should be made for aggregate durability if this option is to be exercised.

Use of Helmholtz Resonators

Several different innovative concepts exist for using pavements with Helmholtz resonators to control tire-pavement noise. Originally developed at the University of Göttingen in Germany, euphonic pavements were designed as “quiet tire/road combination” pavements, incorporating “Helmholtz resonators underneath a perforated but planed aluminum structure” (Sandberg and Ejsmont 2002). Helmholtz resonators are designed to absorb low frequencies, typically ranging between 100 to 250 Hz.

Various models have been evaluated in an attempt to improve the design of the pavement for future implementation as part of an ongoing study by the Silent Road for Urban and Extra-urban Use (S.I.R.R.U.S.) (Sandberg and Ejsmont 2002; Descornet et al. 2000). For example, a two-layer porous asphalt system, in which the underlying layer includes the Helmholtz resonators, has been developed primarily for urban areas. However, this design variation needs further development in order to control the acoustic characteristics of the pavement.

Other Potential Solutions

- Paving concrete that possesses inclusions (e.g., fiberglass, foam, and rubber particles) to increase the acoustical absorption
- Use of acoustically absorptive materials for concrete shoulders (as opposed to traffic lanes), allowing for noise of all sources to be absorbed en route to the receiver and also reducing surface wearing and void clogging issues
- Quiet joint designs, addressing the significant factor of wheel “slapping” at the joints in overall noise levels (Smits 2004)
- Dimpling, waffling, or other innovative geometries of fresh concrete texture
- Textured profile pans, in which a corduroy pattern, for example, might be machined into the profile pan of a slip-form paver to construct a surface similar to that resulting from diamond grinding

3.2. EXPOSED AGGREGATE CONCRETE PAVEMENTS

Although exposed aggregate concrete pavements are commonly used in European countries, the technique has not been routinely used in the United States. Two such projects have recently been reported in Quebec (Thebeau 2004).

Exposed aggregate concrete pavements are commonly constructed using a two-layer “wet on wet” paving process. The top layer thickness typically ranges from 38 to 70 mm (1.5 to 2.75 in.) (Hoerner and Smith 2002), and the mix contains fine siliceous sand and a high-quality coarse aggregate with an ideal maximum size from 6 to 12 mm (0.24 to 0.48 in.) (Buys 2004). Aggregates used in the lower layer of the pavement can be of more modest durability and commonly include recycled materials that help reduce the overall cost of the concrete. Studies have shown that the use of smaller aggregates provided better noise reduction levels (Sandberg and Ejsmont 2002; Hultqvist and Carlsson 2004; Teuns, Stet, and van Keulen 2004; Fults, Yildirim, and Dossey 2004).

The exposed aggregate surface is commonly constructed by applying a set-retarding agent to the newly placed concrete pavement. After a period of time has passed (typically 24 hours), the surface mortar is then brushed and/or washed away from the top of the pavement, exposing a surface of durable aggregates. See Figures 3.1 (Guntert and Zimmerman 2004) and 3.2 (McCormack and Son 2004). When designed and constructed correctly, exposed aggregate concrete pavements have been reported to reduce noise, improve friction, and provide durability equal to that of conventional concrete pavements (Sandberg and Ejsmont 2002; Hoerner and Smith 2002; van Keulen and van Leest 2004; Rens, Caestecker, and Decramer 2004).

Figure 3.1. Surface mortar being washed away to expose aggregates

Figure 3.2. Finished exposed aggregate surface

To be successful, the top layer of the exposed aggregate concrete pavement requires a high-quality concrete. A maximum water-to-cement ratio of 0.38 has been cited, along with a minimum cement content of 450 kg/m³ (758.5 lb./cu. yd.) (Sandberg and Ejsmont 2002). A plasticizer and air entrainer are specified in order to achieve workability and durability. The recommended average texture depth is targeted at 0.9 mm (0.035 in.) to ensure adequate friction (Hultqvist and Carlsson 2004; Henrichson 2004). Exposed concrete with polish-resistant aggregates (polished stone values over 50) should be provided (Sulten 2004; Teuns, Stet, and van Keulen 2004; Fults, Yildirim, and Dossey 2004).

An exposed aggregate concrete pavement with 20-mm (0.79-in.) aggregates in the Netherlands experienced larger noise reductions than an exposed aggregate concrete pavement with a maximum aggregate size of 32 mm (1.26 in.) in Belgium (Hoerner and Smith 2002). Furthermore, it has been reported that an aggregate structure that results in a “plateau with gorges” texture will prove quieter than a texture with “peaks and valleys” (Sulten 2004).

The Dutch province of Noord-Brabant conducted a study intended to further determine the surface characteristics of exposed aggregate concrete pavements (Teuns, Stet, and van Keulen 2004). Various aggregates, texture depths, curing solutions, and concrete finishing techniques were used in the study to determine the combinations that provided optimal performance. Two Dutch aggregates, Dutch stone and Graukwartsiet, were used in the study; the Graukwartsiet possessed a higher polished stone value than the Dutch stone aggregate. Several texture depths were evaluated, with the standard depth considered to be one-quarter of the maximum aggregate size. Different retarding agents were evaluated, including lemon and other acid solutions, along with various combinations of retarding agents and curing compounds. One- and two-layer paving systems, as well as a super smoother (finisher), were also evaluated in the study.

Several key measurements and observations were made after construction. For example, texture depth was found to be affected by the use of a super smoother, which resulted in a maximum texture depth of 1.8 mm (0.07 in.). When not used, texture depths were not as great, with values commonly between 1.1 and 1.6 mm (0.04 and 0.06 in.). The super smoother was shown to produce positive effects in regards to noise emission, possibly due to a reduction in megatexture. The selection of the retarding agent did not appear to make a difference on the results. It was concluded that lower noise levels were measured when smaller maximum aggregates were used.

In a test conducted by the Swedish National Road Administration, several concrete and HMA pavements were tested for abrasion resistance, friction, and noise under heavy traffic (Hultqvist and Carlsson 2004). The test sections were constructed with exposed aggregates in the surface on both jointed plain and continuously reinforced concrete pavements. Two different maximum aggregate sizes were used in the design of the concrete pavements, 8 and 16 mm (0.31 and 0.63 in.). Noise was measured using the close proximity (CPX) method.

In comparison to the hot-mix asphalt pavements constructed on the same job, initial tests revealed that the exposed aggregate concrete pavements with 16-mm (0.63-in.) and 8-mm (0.31-in.) stones provided noise levels that were 1.0 to 1.5 dBA and 3.0 to 3.5 dBA lower, respectively (Hultqvist and Carlsson 2004). The noise emissions of the 16-mm (0.63-in.) exposed aggregate and HMA sections were found to be identical after one year. However, the 8-mm (0.31-in.) exposed aggregate section actually produced quieter noise levels after one year. Three years after construction, the noise levels from all of the pavements had deteriorated. Also of interest was that, during the winter season, concrete pavements produced noise levels about 1 dBA higher than the HMA pavements.

The only large-scale exposed aggregate concrete pavement project in the United States was completed in 1993 on Interstate 75 in downtown Detroit, Michigan (Hoerner and Smith 2002; Kuemmel et al. 2000; Weinfurter, Smiley, and Till 1994; Smiley 1995; Smiley 1996; Smith 2001). This project aimed to demonstrate the effectiveness of the exposed aggregate paving concept along with other technologies identified during a European Scanning Tour on Concrete Pavements.

The exposed aggregate concrete pavement was comprised of a 254-mm (10-in.) jointed concrete pavement constructed in two lifts. The top layer of the pavement was 64 mm (2.5 in.) thick with polish-resistant aggregates, and the bottom layer was 191 mm (7.5 in.) thick with conventional aggregates (Kuemmel et al. 2000; Weinfurter, Smiley, and Till 1994). The lifts were bound using a “wet-on-wet” procedure. A conventional jointed reinforced concrete pavement was constructed nearby as a basis for comparison, textured with transverse tines spaced 25 mm (1.0 in.) apart (Kuemmel et al. 2000; Weinfurter, Smiley, and Till 1994).

Both sections were tested for friction and tire-pavement noise levels. While there was not much difference in friction levels between tests conducted one year and five years after construction, the exposed aggregate concrete pavement did not measure well for noise (Kuemmel et al. 2000; Smiley 1995; Smiley 1996). The section provided a reduction of only 0.4 dBA in exterior noise levels, although similar European projects have claimed noise reductions between 4 and 5 dBA (Smiley 1995).

Researchers believe that the disappointing values may have resulted from too much macrotexture on the exposed aggregate surface, combined with excessive spacing between the coarse aggregate particles. This excessive spacing was a result of large sand particles. Researchers subsequently advised that sand particles larger than 1 mm (0.04 in.) should be eliminated from the top layer of concrete (Smith 2001).

3.3. PERVIOUS CONCRETE PAVEMENTS

Pervious concrete, also known as porous concrete, is a material with large voids that are intentionally built into the mix. The resulting permeability allows for water (and air) to flow readily through this material. This can be seen in Figure 3.3 (Puget Sound Action Team 2004).

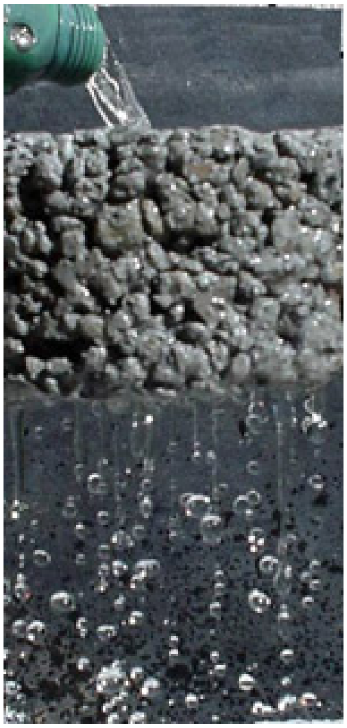


Figure 3.3. Water permeating pervious concrete

When used in highway applications, pervious concrete is typically used as a top layer (wearing course), providing both low noise emission and good drainage capacity (Sandberg and Ejsmont 2002; Beeldens, van Gemert, and Caestecker 2004; Nakahara et al. 2004). The pervious concrete typically overlays a conventional (dense) concrete pavement using a “wet-on-wet” process. Noise reduction in this composite system is a result of the pervious material’s acoustical absorption, while strength and durability are improved by the presence of the underlying concrete pavement layer (Sandberg and Ejsmont 2002). While pervious pavement is used primarily for low-volume facilities, including parking lots, pervious concrete pavements as a single structural layer may also be possible. Much more needs to be understood with respect to its durability under high-volume, high-speed traffic.

Voids in pervious concrete are commonly created by using a gap-graded concrete mix with a sand-to-total aggregate ratio ranging from 5% to 10% (Wu and Nagi 1995). Cementitious materials and/or polymers in the system form a film around the aggregates (for workability) and connect the aggregates together (for strength and durability).

Porosity levels for pervious concrete pavements typically range between 15% and 20% (Sandberg and Ejsmont 2002; Nakahara et al. 2004; Taniguchi and Yoshida 2004; Kagata et al. 2004). In order to attain good noise reduction characteristics, porosity should be at least 25%. Research from Purdue University’s Institute of Safe, Quiet, and Durable Pavements has reported that sound absorption levels were improved when higher porosity was used (Sandberg and Ejsmont 2002; Olek, Weiss, and Neithalath 2004; Olek et al. 2003).

It has also been reported that a relationship exists between sound absorption and aggregate size. In one study, a pavement with decreased aggregate size exhibited improved sound absorption (Olek et al. 2003). A combination of #4 and #8 aggregates in the mixture exhibited improved acoustic absorption characteristics when compared to straight gap grading. However, there may be some difficulty in controlling the gradation of these aggregates. A Belgian study reported sound reduction using pervious concrete as well, with a 5-dBA decrease using a pervious concrete pavement with only 19% porosity (Caestecker 1997).

The U.S. Environmental Protection Agency (EPA) reports that pervious concrete has been known to have a high rate of structural failure, about 75% (U.S. EPA 1999). “Poor design, inadequate construction techniques, soils with low permeability, heavy vehicular traffic, and resurfacing with nonpervious pavement materials” have all shown to be attributing factors to the pavement’s failure (U.S. EPA 1999). Moreover, failures “often resulted in inadequate porosity” (McCormack and Son 2004). However, if pervious concrete pavements are constructed with void contents between 25% and 30%, they have been reported to be structurally sound (U.S. EPA 1999).

Other studies have been conducted to evaluate the durability and noise emission characteristics of pervious concrete (Beeldens, van Gelmert, and Caestecker 2004; Nakahara 2004; Taniguchi and Yoshida 2004). The recommended pervious concrete layer thickness can be calculated according to noise reducing requirements, and in one study this thickness was found to be 40 mm (1.6 in.) for highway applications and 70 mm (2.75 in.) for urban settings (Beeldens, van Gelmert, and Caestecker 2004). The difference is largely related to the speed of the vehicles, which affects the frequency of sound generation, all else being equal. The required porosity is attained by a gap-graded aggregate distribution, in which the particle size is limited to 7 mm (0.28 in.). In order to attain proper strength and durability in terms of freeze-thaw resistance, at least 10% to 12% polymer cement should be used.

When pervious concrete is used as the surface of a two-course pavement, it may be placed using either a “wet-on-wet” or “wet-on-dry” process. In a “wet-on-wet” placement, better adhesion is provided between the layers; with “wet-on-dry” placement, the bonding between the layers can be improved by use of a polymer-cement slurry (Beeldens, van Gelmert, and Caestecker 2004).

Durability is commonly regulated by the interface of the two concrete layers and the presence of pores. Once ice forms at the entrance of small pores and water is unable to move, damage may soon occur. In pervious concrete, freezing tends to originate at the top of the pavement and infiltrate into the lower depths of the layer. Due to differences in the properties of the pervious and dense concretes, stress concentrations at the interface can occur. The damage may take the form of an adhesion loss between the pervious concrete and the conventional concrete (Beeldens, van Gelmert, and Caestecker 2004).

When pervious concrete pavement was first constructed in Belgium, it was found to exhibit undesirable durability in freezing weather (Sulten 2004). Subsequently, polymer additives were used along with a higher cement content. The result was a significant improvement in the service life.

Current policy in Japan is to replace all pavements with pervious systems due to their safety and riding comfort (Nakahara et al. 2004). In order to change over their existing concrete pavements to a pervious system, the most preferable option is thin bonded pervious concrete overlays. Laboratory simulation tests have demonstrated that pervious concrete pavements can resist rutting and have a higher wear resistance to tire chains than porous asphalt.

In a separate study, pervious concrete pavements were evaluated in Japan with two experimental concrete sections, 200 mm (8 in.) in thickness (Descornet et al. 2000). When compared to dense asphalt pavements, they displayed noise reductions of 6 to 8 dBA for dry surfaces and 4 to 8 dBA for wet surfaces. This study was conducted with cars traveling at speeds varying from 40 to 75 km/h (25 to 45 mph). For heavy trucks, noise reduction values were 4 to 8 dBA and 2 to 3 dBA for dry and wet surfaces, respectively.

One disadvantage of using pervious concrete pavements is the clogging of the pavement’s pores. The pores clog over time due to “depositions in the voids of dirt and dust from the road surroundings, from wear products from the pavement itself, and from tires” (Sandberg and Ejsmont 2002).

Continuous maintenance and cleaning can be conducted to help preserve and restore the pavement’s acoustical performance (Beeldens, van Gelmert, and Caestecker 2004). Active cleaning procedures include combination of “water jet blasting, dirt water suction, and vibrations transmitted by a ‘plane of water’ between the water blasting and the suction” (Matsuda, Inagaki, and Masuyama 1998). Pore cleaning can also occur during heavy rainfall and/or when vehicles travel at high speeds. Water is pressurized at the leading edge of the tire-pavement interface, and dirty water is removed, by suction, at the trailing edge. The result is a self-cleaning effect.

Double-layer pervious concrete has also been demonstrated as a possible solution, where a top lift with smaller aggregates is placed over a larger stone mix. The resulting system may help to minimize infiltration of debris that causes clogging (see Figure 3.4).

Figure 3.4. Double-layer pervious concrete

The added cost of constructing pervious concrete pavement must be taken into consideration. The long-term effectiveness of this technique is also still under debate. In one report by the Belgian Road Research Centre, “extra costs as compared with a conventional concrete 22-cm (8.7-in.) thick as compared to a 4-cm (1.6-in.) pervious concrete laid over 18 cm (7 in.) of conventional concrete are estimated … as roughly 40%” (Descornet et at. 2000). However, “no significant cost difference with an equivalent structure including porous asphalt” was found (Descornet et al 2000). The cost of constructing quiet pervious concrete pavements in New Zealand has been reported at US$132 per m² (US$111 per sq. yd.) (Clarke 2004). In the United States, pervious concrete projects have been reported to cost an additional 40% (Jacklet 2004).

4. Field Measurements of Tire-Pavement Noise with Respect to Texture

In January 2005, the ACPA joined with the CP Tech Center and the FHWA to help organize and implement a comprehensive field experiment plan to evaluate and compare current surface characteristics practices. The project team initially thought that a sufficient understanding of the capabilities of conventional methods would be covered through the evaluation of current European and U.S. methods. However, at the November 2004 workshop it was concluded that there was an urgent and critical need to provide short-term solutions using existing technologies. It was determined that in order to accomplish this, immediate field experiments were needed to determine the conventional surface textures that were the quietest and that could be repeatedly and consistently built. Thus, the field evaluation portion of the project was established.

The objective of the initial field evaluation is to measure and analyze conventional texturing variations and grinding techniques and their respective surface characteristics, particularly with respect to tire-pavement noise. Measurement techniques and data analysis are described in this section. While data collection and analysis are ongoing at the time of this writing, preliminary texture-noise measurement conclusions are included in section 5.

4.1. MEASUREMENT TECHNIQUES

As part of the field evaluation, the project team is evaluating the accuracy and reproducibility of various conventional and new measurement technologies. Several important recent advancements to measurement equipment and approaches are discussed below.

RoboTex Line Laser Technology

The project team developed and implemented a robotic texture measurement system (RoboTex). RoboTex is a six-wheeled, remote control robot that provides three-dimensional (3D) texture information for concrete pavement surfaces through the use of LMI Selcom’s innovative RoLine line laser. See Figure 4.1. Traditional lasers that measure texture and smoothness rely on a single-point laser that captures elevations along a single path on a roadway. The line laser projects a laser line approximately 100 mm wide, with the ability to capture 100 or more elevations across the entire line at a rate of 1 kHz. The mounted laser runs along a road surface at walking speed, thus creating a 3D texture map with a lateral resolution of 0.5 mm to 1.0 mm, and a vertical resolution of 0.01 mm. See Figures 4.2 and 4.3.

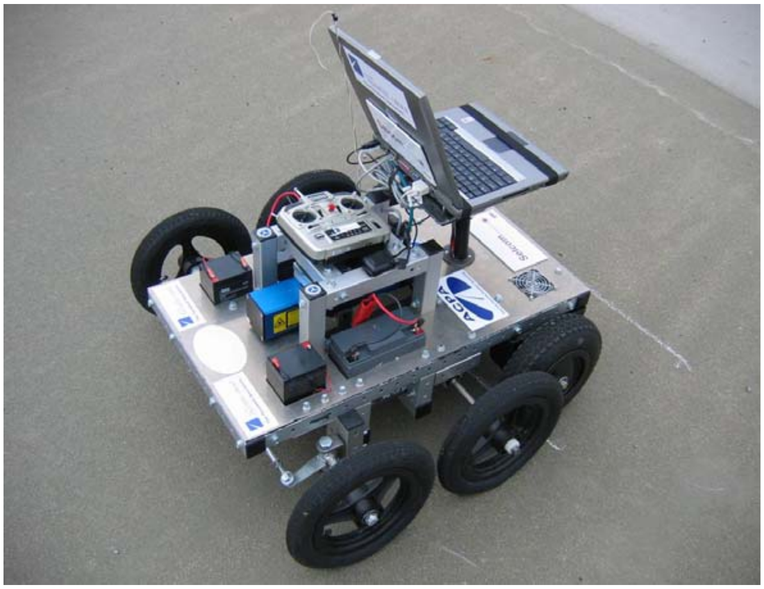
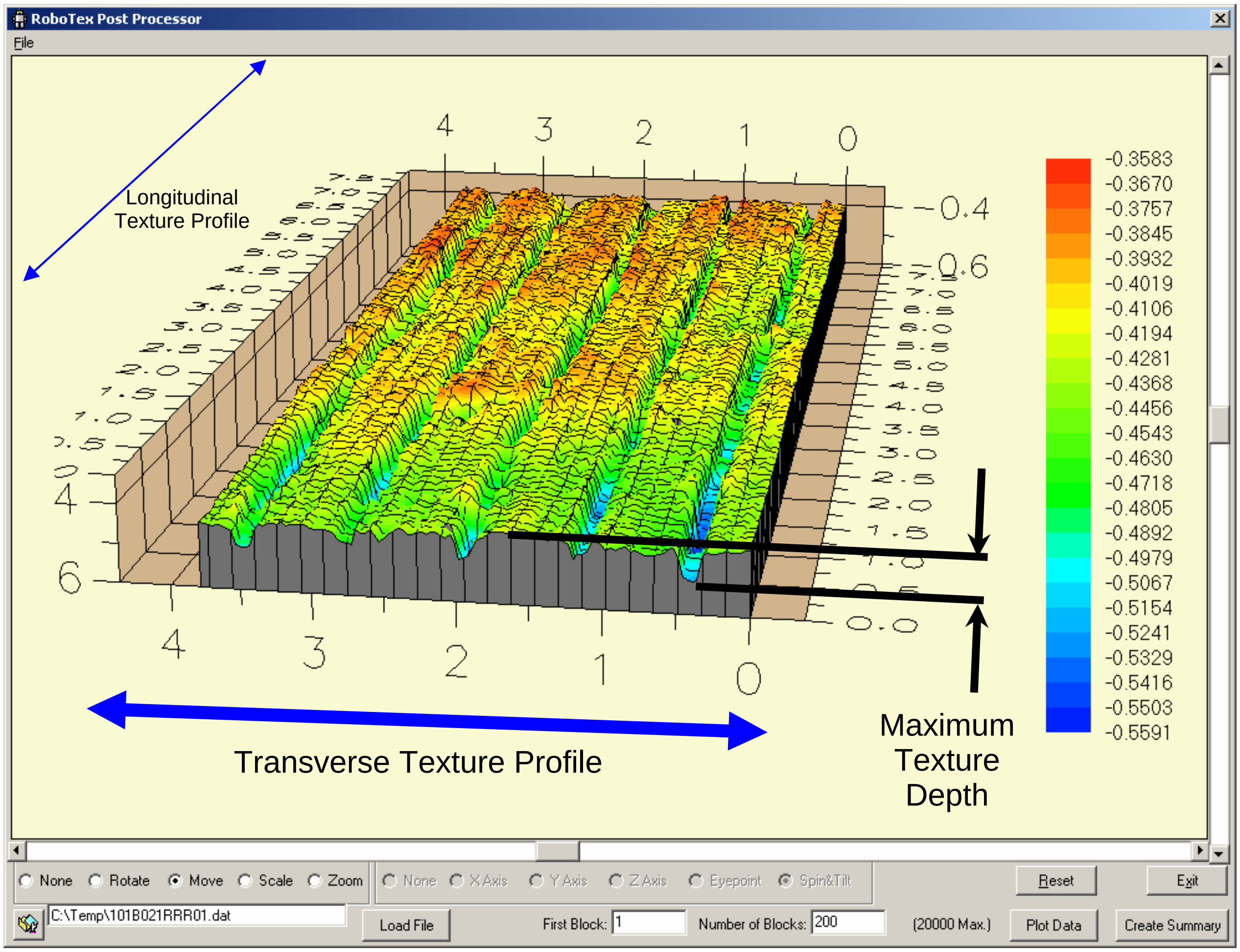


Figure 4.1. RoboTex with laser line technology

Figure 4.2. RoboTex in operation



○ None ○ Rotate ● Move ○ Scale ○ Zoom

○ None ○ X Axis ○ Y Axis ○ Z Axis ○ Eyepoint ● Spin&Tilt

C:\Temp\101B021RRR01.dat

First Block: 1

Number of Blocks: 200 (20000 Max.)

Figure 4.3. RoboTex software data presentation

Nominal vs. Actual Texture

Texture width and depth often vary appreciably from what is specified, such that nominal texture is not the same as actual, as-constructed texture. From the RoboTex measurements, it has been proven that the as-constructed width-depth-spacing of the texture is different from the specified, even under controlled conditions. In further research, the texture will be adjusted to actual, as opposed to nominal, which appears to be of little significance.

Quality Control of Texture during Construction

Field trials need to be conducted to establish best practices for texturing quality control. More advanced control of the operations may be needed via electronic sensing of as-constructed texture. Texture measurements during construction operations will probably have to go beyond the sand patch test if variability is to be controlled effectively. Depth or pressure sensors may need to be included on the texture equipment to provide the feedback necessary to decrease variability. A line laser mounted on the equipment is another option, with software that provides clear feedback to the texture operator about the corrections to make. Only with revised measures of texture will the concrete pavement industry more adequately be able to ensure that a quieter pavement is being constructed.

On-Board Sound Intensity (OBSI) Repeatability and Corrections

On-board sound intensity (OBSI) measurement includes paired microphones that allow for directionalized measurement. See Figure 4.4. OBSI measurements have been shown to be repeatable based on replicate sampling. Standard errors between replicate runs are typically from 0.02 to 0.4 dBA.

Figure 4.4. OBSI measuring device

The project team developed environmental correction factors for OBSI. While not routinely applied to OBSI data in the past, the environmental factors were found to be very significant in some cases given the wide range of climates and altitudes being encountered. As an example, measurements of an identical pavement in Colorado in the summer differ from those taken in Iowa in the winter by more than 2.1 dBA. With these correction factors calculated and applied properly, valid comparisons can now be made between different locations.

Traffic Noise Model

In future work, pavement texture and OBSI data will be linked to the measurement techniques used in the FHWA Traffic Noise Model (TNM) to determine noise impacts on abutters. Advanced modeling will be used to determine of the impact that various levels have on noise abatement for abutters.

4.2. DATA COLLECTION

The field evaluation of techniques for texturing and grinding includes data collection for three types of pavement project sites:

- Type 1. New construction
- Type 2. Existing but relatively new sites, or sites of historical significance
- Type 3. Existing sites of all ages

Type 1 includes new construction, multiple texture configurations, with pre-traffic, post traffic, and periodic in-service measurements collected until texture and noise measurements stabilize (possibly two to five years). Data collection includes a full suite of noise, texture, friction, and smoothness measurements, along with concrete and construction properties.

Type 2 includes in-service pavements and relatively new and/or significant projects with one or more texture configurations. In-service measurements will be performed until texture and noise measurements stabilize. Data collection includes a full suite of noise, texture, friction, and smoothness measurements, along with concrete properties, as available. Type 3 includes in-service pavements of any age. Noise and texture measurements will be collected one time only.

The plan called for up to two Type 1 sites for new construction using conventional texture variations, two Type 1 sites with grinding variations, up to eight existing Type 2 projects with comprehensive analysis, and up to 24 additional Type 3 sites with noise and texture measurements only. The data collection completed as of this date includes the following:

- 1 Type 1, 8 Type 2, and 19 Type 3 projects
- Sites in CO, ND, MN, IA, AL, GA, NC, VA, KS, WI, OH, IN, MI, NY, MO, and Quebec
- 213 unique nominal pavement textures, including
    - 71 transverse tining (including 6 skewed)
    - 51 longitudinal tining (including 1 sinusoidal)
    - 1 cross-tined (transverse and longitudinal)
    - 20 diamond ground
    - 8 grooved (2 longitudinal, 6 transverse)
    - 30 drag (burlap, turf, broom, belt, and carpet)
    - 1 transverse broom
    - 3 exposed aggregate
    - 3 shot peened
    - 1 milled
    - 19 HMA
    - 5 surface treatments
- 547 unique test sections, averaging 250 ft. each, for a total of 143,000 ft.

5. Conclusions

While consistent reliable information regarding texture and noise is still being collected and analyzed, some preliminary conclusions can be made from U.S. and European experience and field measurement data collected to date.

Table 5.1 provides a summary of various concrete pavement texture options (ACPA 2000) along with some notes about their use and perceived effectiveness in reducing tire-pavement noise. Research is ongoing to further evaluate the surface characteristics achievable with these textures.

Table 5.1. Summary of various concrete pavement texture options

Texture	Description	Current Use and Perception
Artificial turf drag	Produced by dragging an inverted section of artificial turf from a device that allows control of the time and rate of texturing, usually a construction bridge that spans the pavement; typically produces 1/16 to 1/8 in. deep striations.	Artificial turf drag textures have been shown to provide sufficient friction characteristics for many roadways, as well as reduced noise relative to many transversely tined pavements. Minnesota has used this type of texturing as a cost-effective method to reduce tire-pavement noise on high-speed roadways.
Burlap drag	Produced by dragging moistened coarse burlap from a device that allows control of the time and rate of texturing, usually a construction bridge that spans the pavement; typically produces 1/16 to 1/8 in. deep striations.	Burlap drag textures have been shown to provide sufficient friction characteristics for many roadways, especially those with speeds less than 45 mph, as well as reduced noise relative to many transversely tined pavements. Germany has used this type of texture on its high-speed Autobahn system.
Transverse tining	Achieved by a mechanical device equipped with a tining head that moves across the width of the paving surface laterally or on a skew. It is important to maintain a consistent concrete mixture and move the paving train forward constantly at a uniform rate of speed for consistent tining depth. Most agencies precede with an artificial turf or burlap drag texture.	For tined pavements, texture depth and groove width are important parameters in tire-pavement noise generation. Pavements with uniformly spaced transverse tining generally, but not always, exhibit undesirable “wheel whine” noise (Kuemmel 1997).
Longitudinal tining	Achieved by a mechanical device equipped with a tining head (metal rake) pulled in a line parallel to the pavement centerline. It is important to maintain a consistent concrete mixture and move the paving train forward constantly at a uniform rate of speed for consistent tining depth. Most agencies precede with an artificial turf or burlap drag texture.	Tined texture depth and groove width are important parameters in tire-pavement noise generation. Longitudinal tining is more often quieter than transverse tining. Narrower tine spacings might be used to reduce vehicle tracking and possibly reduce noise even further. Lateral stability of narrow-tired vehicles may also benefit from this.
Diamond grinding	Longitudinal, corduroy-like texture made by equipment using diamond saw blades gang-mounted on a cutting head. The cutting head typically produces 50–60 grooves/ft. and can remove 1/8–3/4 in. from the pavement surface.	Although diamond grinding has traditionally been used to restore pavement smoothness, this method has also been shown to reduce tire-pavement noise and improve friction in the short term. Diamond ground pavements do not affect vehicle tracking as much as widely spaced longitudinally tined pavements.
Exposed aggregate concrete pavement	European practice includes applying a set retarder to the new concrete pavement and then brushing or washing away mortar to expose durable aggregates. Other techniques involve the uniform application of aggregates to the fresh concrete.	Exposed aggregate concrete pavement surfaces are regarded as an effective method for reducing tire-pavement noise while providing adequate friction. Smaller aggregate sizes have been reported to provide larger noise reductions, while aggregates with a high polished stone value increase durability. Only one large-scale exposed aggregate concrete pavement has been built in the United States.
Pervious concrete pavement	When used in highway applications, pervious concrete is typically used as a top layer (wearing course), providing both low noise emission and good drainage capacity (Sandberg and Ejsmont 2002; Beeldens, van Gemert, and Caestecker 2004; Nakahara et al. 2004). The pervious concrete typically overlays a conventional (dense) concrete pavement using a “wet-on-wet” process.	Sound absorption levels for pervious concrete pavements have been shown to increase with higher porosity levels. Quieter pervious concrete also results from smaller aggregate sizes. Use of pervious concrete pavements for high-volume, high-speed facilities is still in its infancy and will likely require years of experimentation before the requisite confidence can be gained in this application. Regular maintenance and cleaning may be needed to prevent clogged pores and to preserve the pavement’s acoustical performance. Research on durability is ongoing in wet, hard-freeze areas.

5.1. PRELIMINARY FIELD MEASUREMENTS

Examples of 3D texture profiles and average OBSI levels for various concrete pavement surfaces are presented in Figures 5.1–5.10. Figure 5.11 presents the preliminary noise-texture catalog, with bars representing variability and circles representing the average. It is important to note these are nominal textures and that the study’s field data collection and analysis are ongoing.

It should also be noted that while trends are evident, there are often exceptions. This evaluation has reinforced how it is not possible to relate specific texture geometry—width, depth, and spacing—to tire-pavement noise. It is clear that more work is needed to establish better ways of quantifying texture.

Texture Geometry and Noise Levels

For a preliminary understanding of the texture-noise results to date, nominal texture data have been sorted from quietest to loudest. The general population of concrete pavement textures included range from a low end of approximately 100 dBA to a high end of 113 dBA based on average OBSI levels measured in decibels. The large differences are attributed to differences in texture configurations and surface conditions. It should be noted that an increase of 10 dBA can often represent a doubling of perceived sound.

There appears to be a strong relationship between texture depth and tire-pavement noise. However, this statement in and of itself is an oversimplification and falls short of truly characterizing the relationship between texture and noise. This relationship may have more to do with the fact that a deeper (more aggressive) texture causes more disturbances of the concrete surface and thus leads to random deposits of concrete on the surface that, in turn, increase noise.

The tire-pavement noise data to date rank drag and grinding among the quieter textures and transverse tining among the loudest, based on average OBSI levels for these nominal texture types. Many texture subsets within each class must still be analyzed. The averaged noise rankings do not always hold true, especially given the variability present.

Based on the data collected to date, this is close to the range of noise values representing the total population of concrete pavements in the country. There may be other concrete pavements above 113 dBA, but 98–100 dBA will likely be close to the quietest concrete pavements textured using conventional technologies.

Texture Variability

Measurement of texture variability was made possible with RoboTex measurement system based on the LMI Selcom sensor. The texture and noise variability observed within a section for tining—particularly transverse tining—is generally higher than the standard deviation for drag or ground textures. Preliminary analyses of variability shows wide overlap between texture types, with even some transverse tining sections actually quieter than some longitudinally tined surfaces. Subtle variations in texture geometry appear to have an appreciable influence on noise at the tire-pavement interface.

A guide specification will be developed in future work to address the variability issue and ensure the loudest textures are avoided. Guidelines for new texture specifications may need to focus on controlling the texture configuration so as not to allow a certain percentage of tire-pavement noise values above a certain threshold. This would control the average and the variability.

Texture Wear Rate

Texture wear varies by mix. On one specific case using a softer, sandier mix (Kansas Type 2 project), the texture wear on a led to a 1 to 2 dBA drop in tire-pavement noise after only one year in service. Snow plowing and environmental effects, in addition to traffic volume, appear to have a significant impact on the wear rate. This was found by analyzing the pavement between the wheel paths.

Weather Data

In the Iowa data collection, weather data were collected during each test section, along with the tining depth measurements. It was found that the weather may have contributed to the shallow tining depths. On most days, the air was hot and humid, causing the concrete to set faster. This caused the surface of the slab to be too dry for the tines to be placed deeply enough.

5.2. NOISE ZONES

The project team has divided the average OBSI data to date into three zones to help frame a preliminary interpretation of findings:

- Zone 1: Low Noise Level or “Innovation” Zone (up to ~99/100 dBA)
- Zone 2: Mid Noise Level or “Quality” Zone (~99/100 to ~104/105 dBA)
- Zone 3: High Noise Level or “Avoid” Zone (~104/105 dBA and above)

Figure 5.11 illustrates the zone concept with the nominal concrete pavement texture data; Figure 5.12 includes examples of asphalt texture types. OBSI levels of specific nominal texture type categories are presented in more detail in Figures 5.13–5.16. Note that bars represent variability, and circles represent the average.

It is important to note that while the zones are distinct, the borders are not. The zone borders, while muted, help to break down the data into manageable portions. The zone concept can be used to help interpret the noise data and craft solutions that include both research and policy considerations.

One approach in establishing the zones was to examine tire-pavement noise as it relates to noise policy and the FHWA Traffic Noise Model (TNM). Currently, the TNM requires the use of an “average” pavement type in the analysis for potential noise abatement. It is estimated that the OBSI value that corresponds to the “average” pavement type lies within Zone 2. This means that those pavements that are louder than “average” are inherently benefited, while those that are quieter are penalized. Discussions are currently underway about the possibility of “unlocking” the pavement type within TNM. If this were to happen, there would be immediate demand for concrete pavement solutions that are initially and throughout their life in the lower end of Zone 2 and possibly in Zone 1. Furthermore, a targeted effort would be needed to reduce the noise level of those existing pavements in Zone 3.

Another approach in establishing zones is to look at today's concrete pavement operations and to determine what is feasible based on available technology and the state of the practice. What would be the impact on the sum total of all surface characteristics if future texturing and grinding operations of conventional concrete pavements were specified to fall in Zone 2? What is causing the high noise level and/or those irritating frequencies in the Zone 3 pavements? What distinguishes the same nominal texture from being loud or quiet based on the distribution and deviations of the texture itself? If friction is not compromised, immediate work should focus on constructing and maintaining textures in the lower portion of Zone 2.

The zone concept also establishes Zone 1 as a target for the future. Can/should the industry develop a quieter pavement for those situations and locations where owners demand ultra-quiet solutions? Will drivers and abutters continue to demand even quieter pavements in the future? One long-term challenge to the industry is to have available non-standard solutions.

Zone 1

Zone 1 is the low noise level or "innovation" zone, with OBSI values in the ~99/100 dBA and below range. With the exception of some experimental pervious concrete pavements, there are no existing concrete solutions in Zone 1. It appears that conventional (dense) concrete may not have the ability to be built consistently in Zone 1. It has been demonstrated that in rare circumstances small portions of some in-service concrete pavements do fall within the Zone 1 range. Research and innovation will therefore be required to develop solutions that consistently provide OBSI levels within the zone.

Asphalt solutions in Zone 1 include porous asphalt, asphalt crumb rubber, and a few stone matrix asphalts and dense-graded asphalt mixes. The lowest recorded pavement noise level to date is approximately 93 dBA, from a double-layer porous asphalt. In the United States, crumb rubber products have had initial values of 96 dBA. These values were determined for relatively new pavements only; note that texture characteristics including noise levels often changed dramatically over time.

What is clear from evaluating the data collected so far is that the concrete paving industry may be at a practical low limit for conventional concrete pavement products and practices without moving toward more innovative solutions. Zone 1 should be the target for conditions that merit particularly low noise solutions.

In order to move into the low-noise Zone 1, the concrete pavement industry will have to embrace innovative solutions such as increasing porosity, minimizing adverse texture wavelengths, or even modifying mechanical properties, including stiffness. Successful products may include the use of pervious concrete, inclusions, and polymers. Negative textured pavements are probably the only solution in Zone 1.

Providing products in this zone will require some careful crafting of an experimental plan with adequate funding, a smart relationship with industry and innovative DOTs willing to experiment in this area. Pervious concrete is the likely candidate for first successes in this area. A plan for advancing pervious concrete pavement solutions is included in Appendix C.

Zone 2

Zone 2 is the mid noise level or “quality” zone, with OBSI values approximately in the 99/100 to 104/105 dBA range. The target for both new and existing concrete pavements should be in this zone. The zone represents textured concrete pavement solutions that provide a balance of noise, friction, smoothness, and cost effectiveness.

It has been found that any type of nominal texture can provide solutions in this range. This includes drag textures, grinding, longitudinal tining, and even transverse tining. With diligent quality control, new pavements can consistently be built below 103 dBA. Grinding and burlap/turf drags often result in “quality” decibel levels and may provide the easiest method to attain these values. Many solutions, even including some transverse tining, exist to achieve noise values on the high end of Zone 2, between 103 and 105 dBA.

In future study, the impact of tire-pavement noise on the FHWA TNM will be evaluated. Advanced modeling will be used to determine of the impact that 103–105 dBA OBSI levels have on noise abatement for abutters.

Variability, however, has been found to be too high for all types of textures in this zone. If noise is a payment consideration (directly or through texture), there is too high of a risk of missing specification targets, assuming use of a percent within limits approach. Once the texture is selected, the key is to place it consistently.

For particularly noise-sensitive solutions, joint effects on noise should be considered, especially to eliminate downstream noise increases. Thin (single) cut joints should be used. If believed to be necessary, joint sealant should be applied uniformly and without any protrusion above the pavement surface.

As grinding and drag texturing are two currently available solutions with the best potential for achieving 99–103 dBA OBSI levels, the following steps should be considered to better understand and optimize their use:

- For grinding, a connection needs to be made between the blade spacing/width on the drum and the actual in-place texture. The as-ground texture is not the same on all concretes, even for the same drum. Data on as-ground texture vs. the drum configuration need to be analyzed, particularly as the texture relates to mix type and how it wears over time. The interrelationships between noise, friction, and smoothness also need to be explored. With these improvements in the understanding of diamond ground texture and noise levels, grinding should be able to be practiced consistently within Zone 2, assuming reasonable diligence to detail.

- For drag solutions, the focus should be on texture and friction durability as a function of mix type. One possible innovative solution is to consider two-course construction with

> the thin lift on top using premium aggregates and high-quality texturing control. This could provide a solution at the lower end of Zone 2. It should be noted that both the Minnesota Department of Transportation and, until recently, Germany have used drag/turf textures on high-speed facilities (Germany recently moved away from burlap drag due to the loss of texture on some of their pavements).

Zone 3

Zone 3 is the high noise level or “avoid” zone, with OBSI values in the range of ~104/105 dBA and above. This zone includes highly variable textured pavement, very aggressive transverse textures, and older pavements with serious joint deterioration. A significant amount of existing concrete pavements in the United States fall within this range. Drivers and abutters are being conditioned to think that concrete is loud as a result. (These loud examples are contributing to “it’s too noisy” being added to the list of erroneous perceptions about concrete pavements.)

The concrete paving industry must avoid building any pavements in this zone and should work to eliminate existing pavements from this zone through grinding or other options, starting with the worst first.

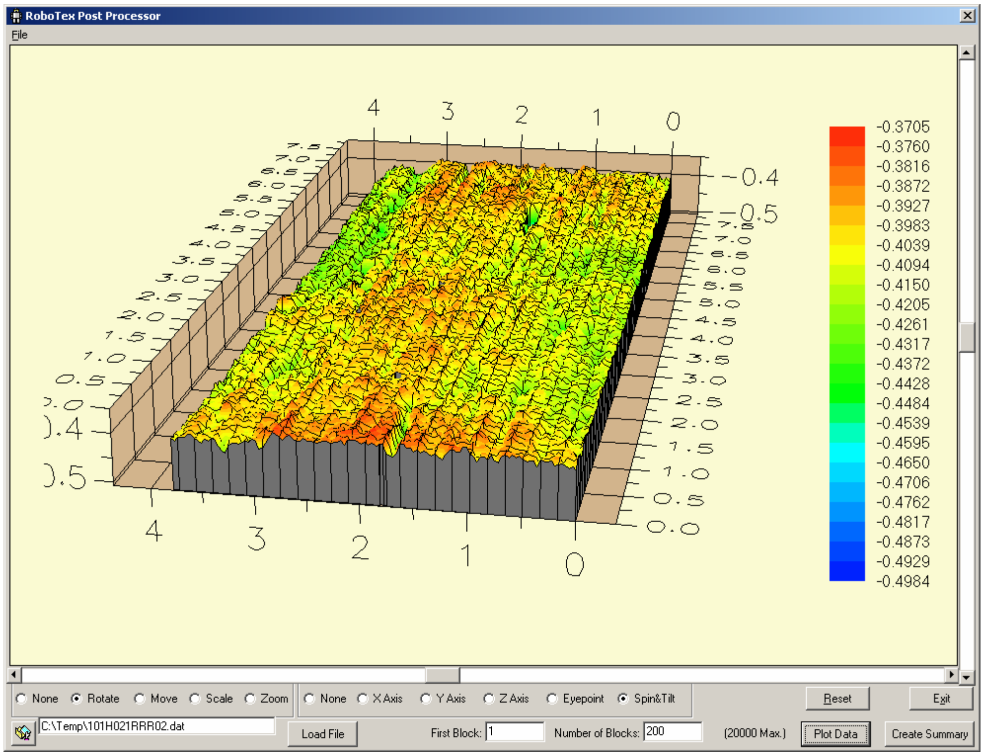
The elimination of the worst first should include a consideration of the frequency issues as well, as opposed to pure decibels. For example, eliminating “the whine” in this zone may be just as important as eliminating the decibels. This approach requires an inventory of existing pavements.

Joint issues are probably playing a big part in the psychoacoustics of existing pavements in this zone. An elimination of the loudest first would have to include joint repairs as well (e.g., dowel bar retrofitting and grinding).

In any program to eliminate pavements in this zone, a balance of noise, friction, and smoothness should be examined. Lowering noise can be coupled with restoration of friction and smoothness. There should be no compromise in safety in any solution.

Diamond grinding can be used to provide quieter pavements that retain features such as sound qualities (acoustic durability) and skid resistance for many years. Diamond grinding of concrete pavements to address noise concerns has proven successful. In Arizona, grinding of concrete pavement surfaces has reduced noise source levels up to 9 dBA relative to some transversely tined surfaces. The noise level reduction is dependent on the number of trucks, since the percent of the noise related to tire-pavement interface is less with more trucks in the traffic stream.

If pavements are in need of structural enhancement, concrete overlays may provide an option. The noise characteristics can be addressed at the same time as the structural elements. As the overlay is being constructed, the new surface texture should be chosen to address the noise concerns. Depending on the speed limits, the appropriate texture could be created by turf or heavy burlap drag or could be longitudinally tined.



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Number of Blocks: 200

Figure 5.1. Heavy burlap drag texture

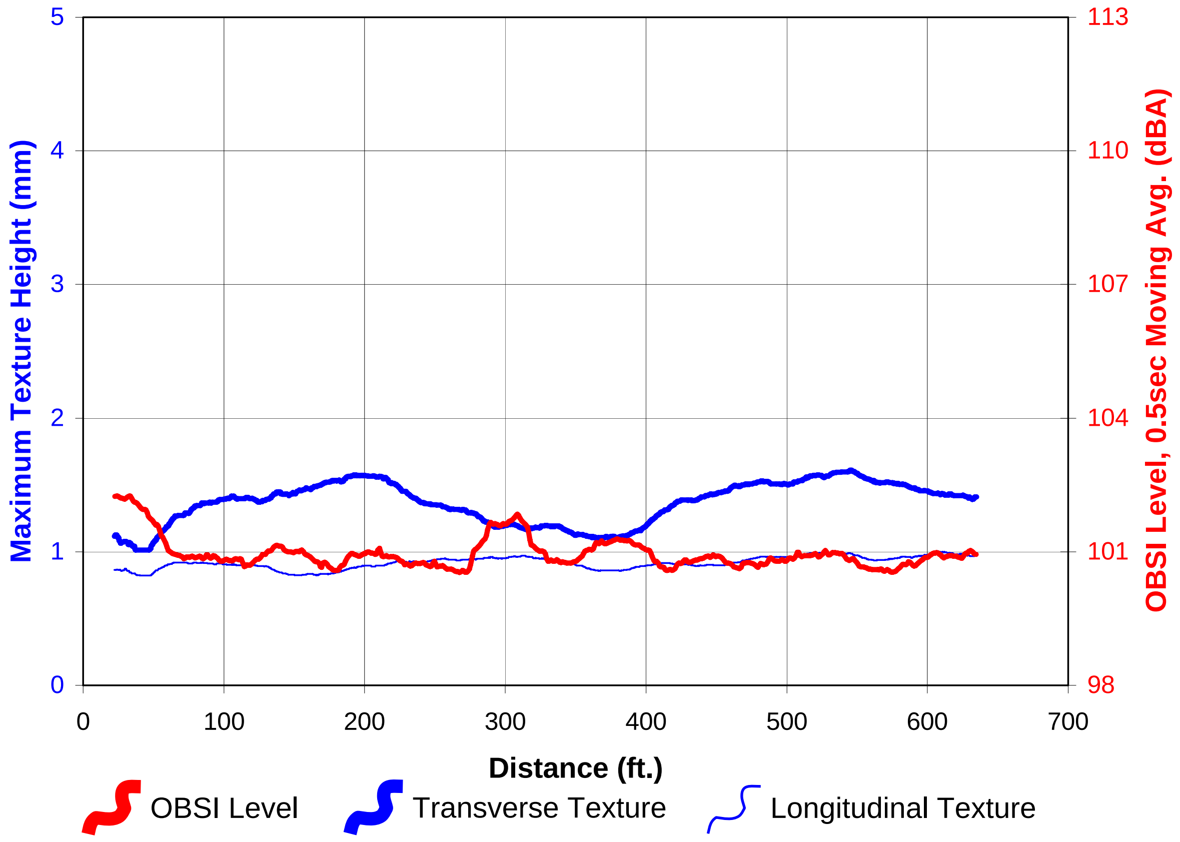
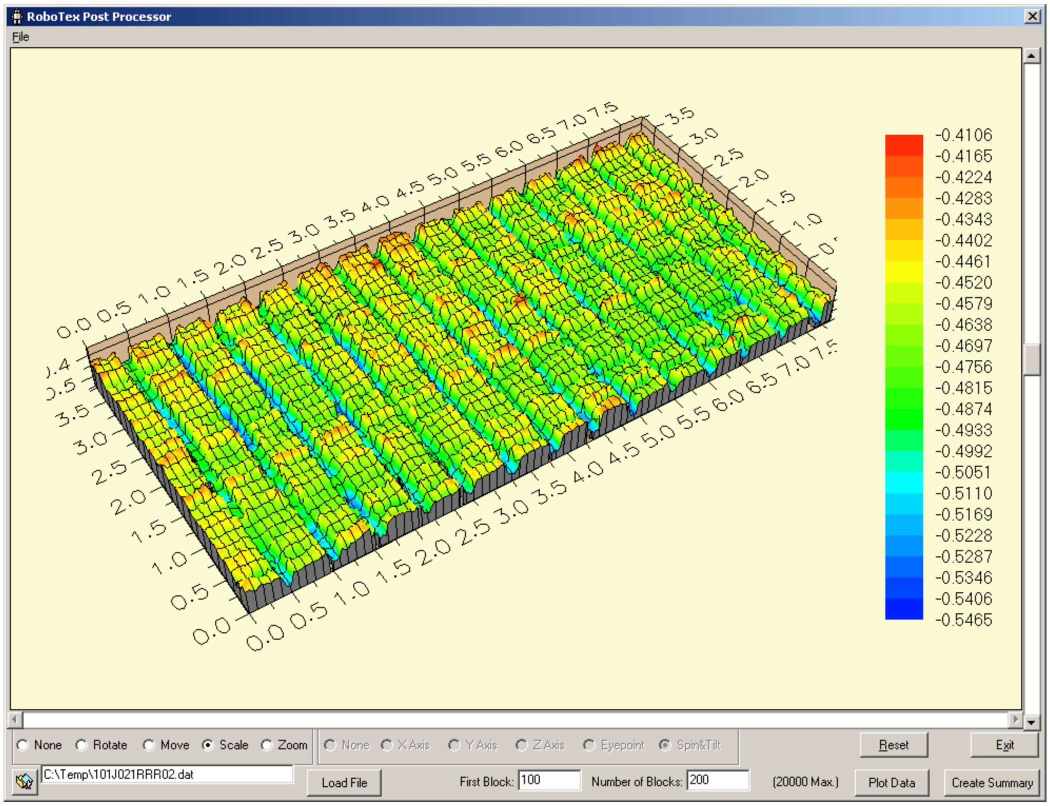


Figure 5.2. Preliminary reporting of texture vs. OBSI level for heavy burlap drag



● Scale

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Number of Blocks: 200

Figure 5.3. Uniform transverse tine + burlap drag texture

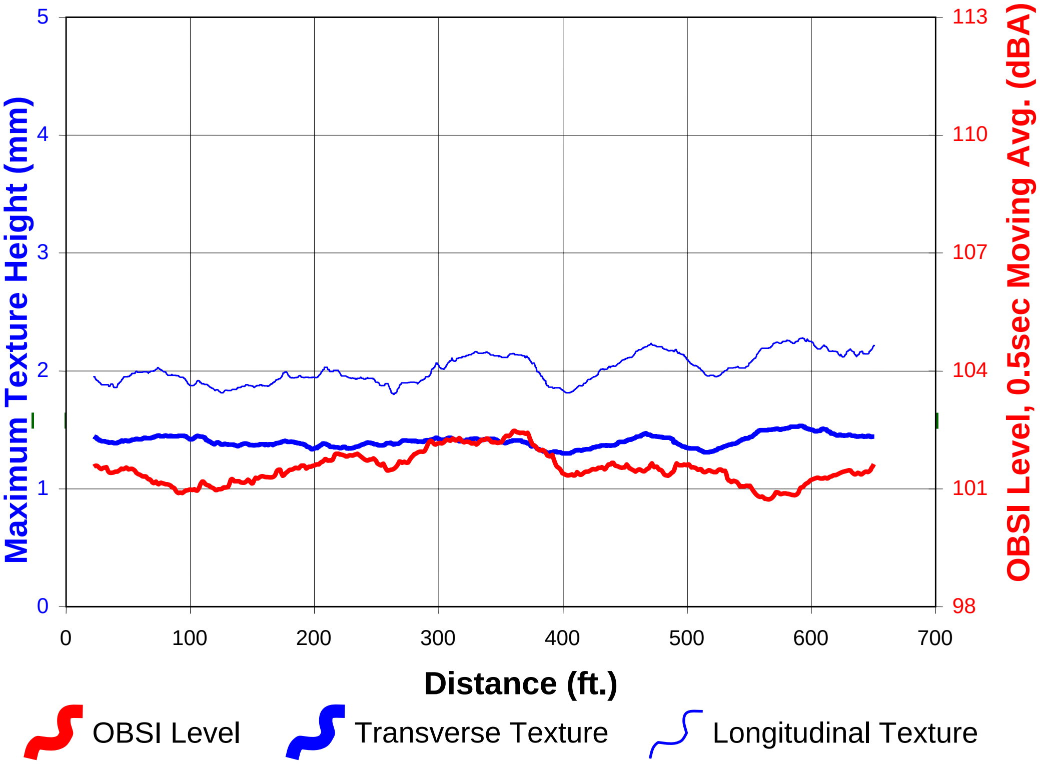
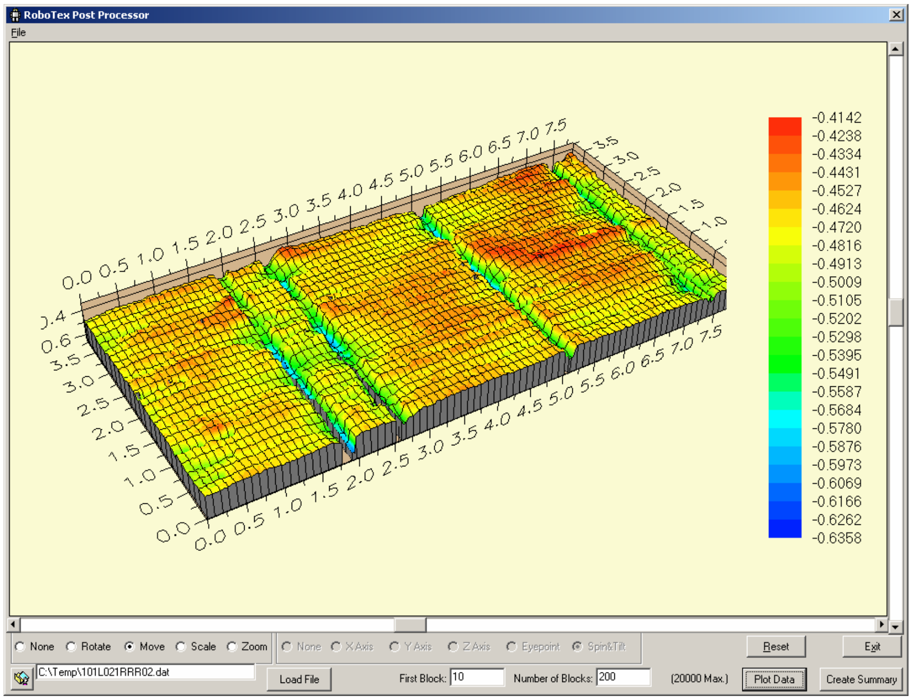


Figure 5.4. Preliminary reporting of texture vs. OBSI level for uniform transverse tining



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Number of Blocks: 200 (20000 Max.)

Figure 5.5. Random transverse tine + burlap drag texture

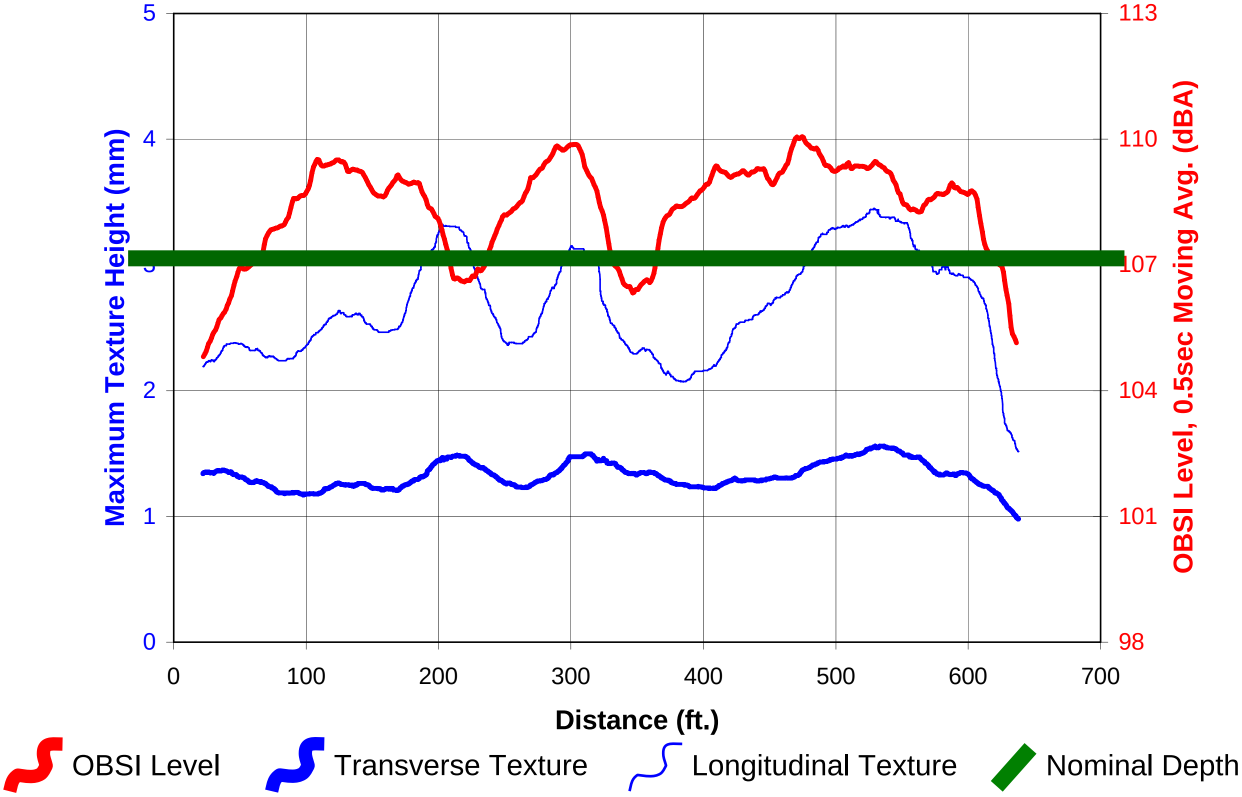
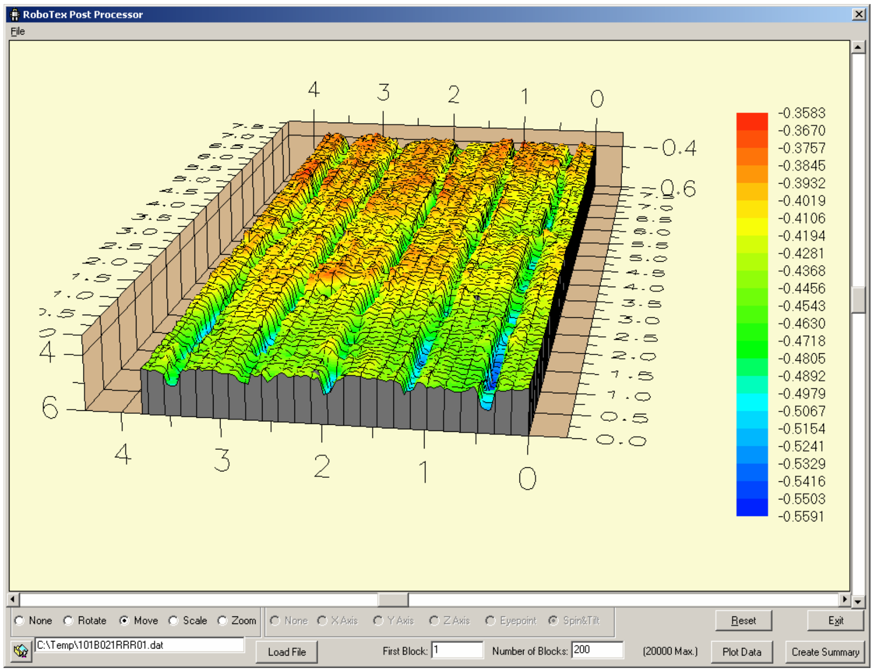


Figure 5.6. Preliminary reporting of texture vs. OBSI level for random transverse tining



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First Block: 1
Number of Blocks: 200 (20000 Max.)

Figure 5.7. Longitudinal tine + burlap drag texture

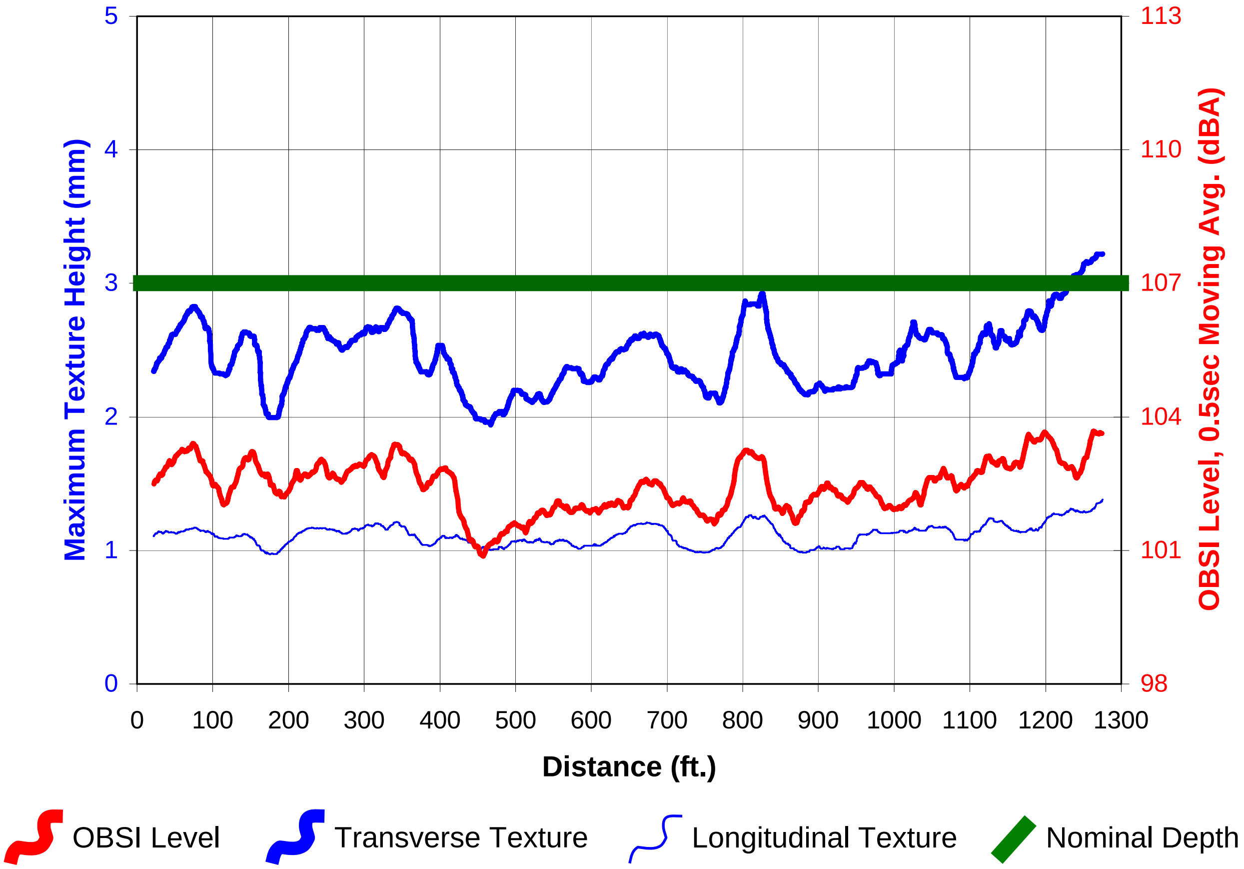
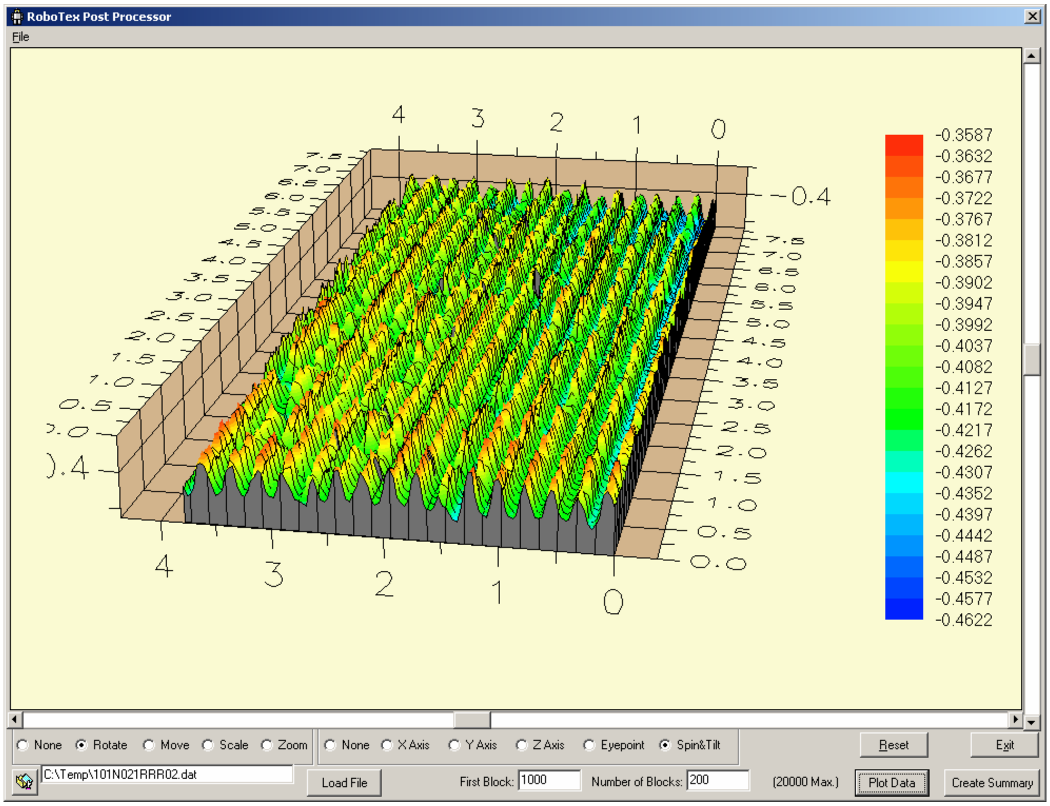


Figure 5.8. Preliminary reporting of texture vs. OBSI level for longitudinal tining



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○ None ○ X Axis ○ Y Axis ○ Z Axis ○ Eyepoint ● Spin&Tilt

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Number of Blocks: 200

(20000 Max.)

Figure 5.9. Diamond ground texture

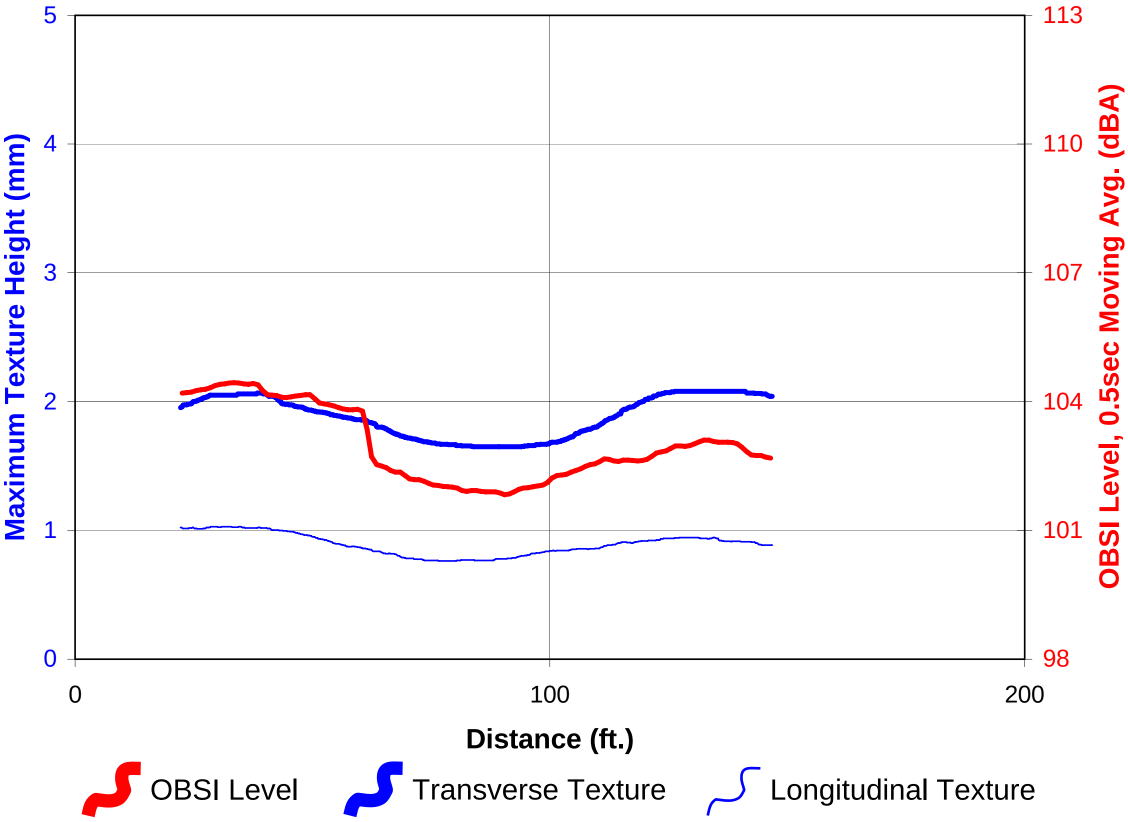

Figure 5.10. Preliminary reporting of texture vs. OBSI level for diamond ground texture

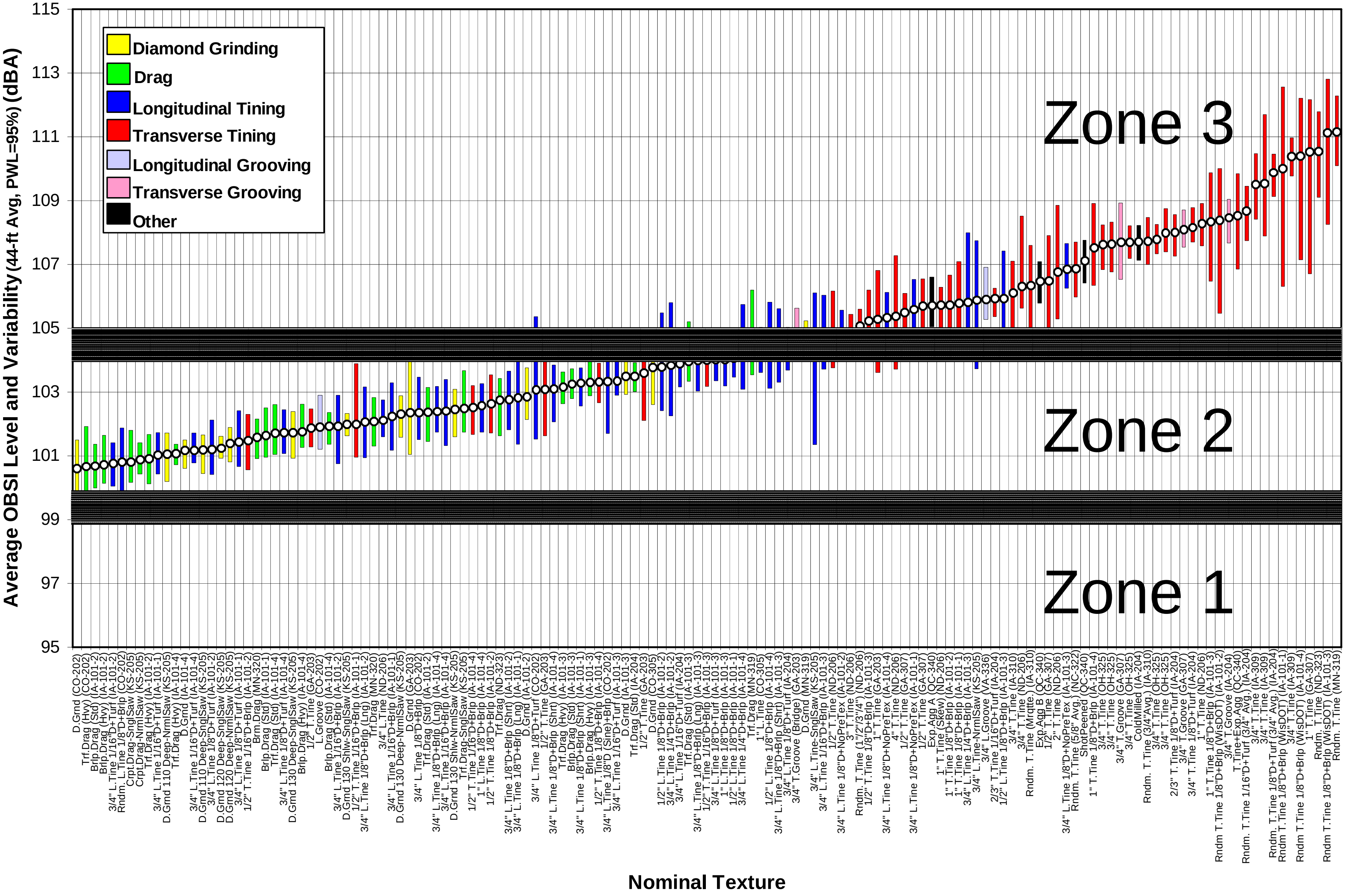

Figure 5.11. Preliminary catalog of pavement texture vs. average OBSI level with noise zones

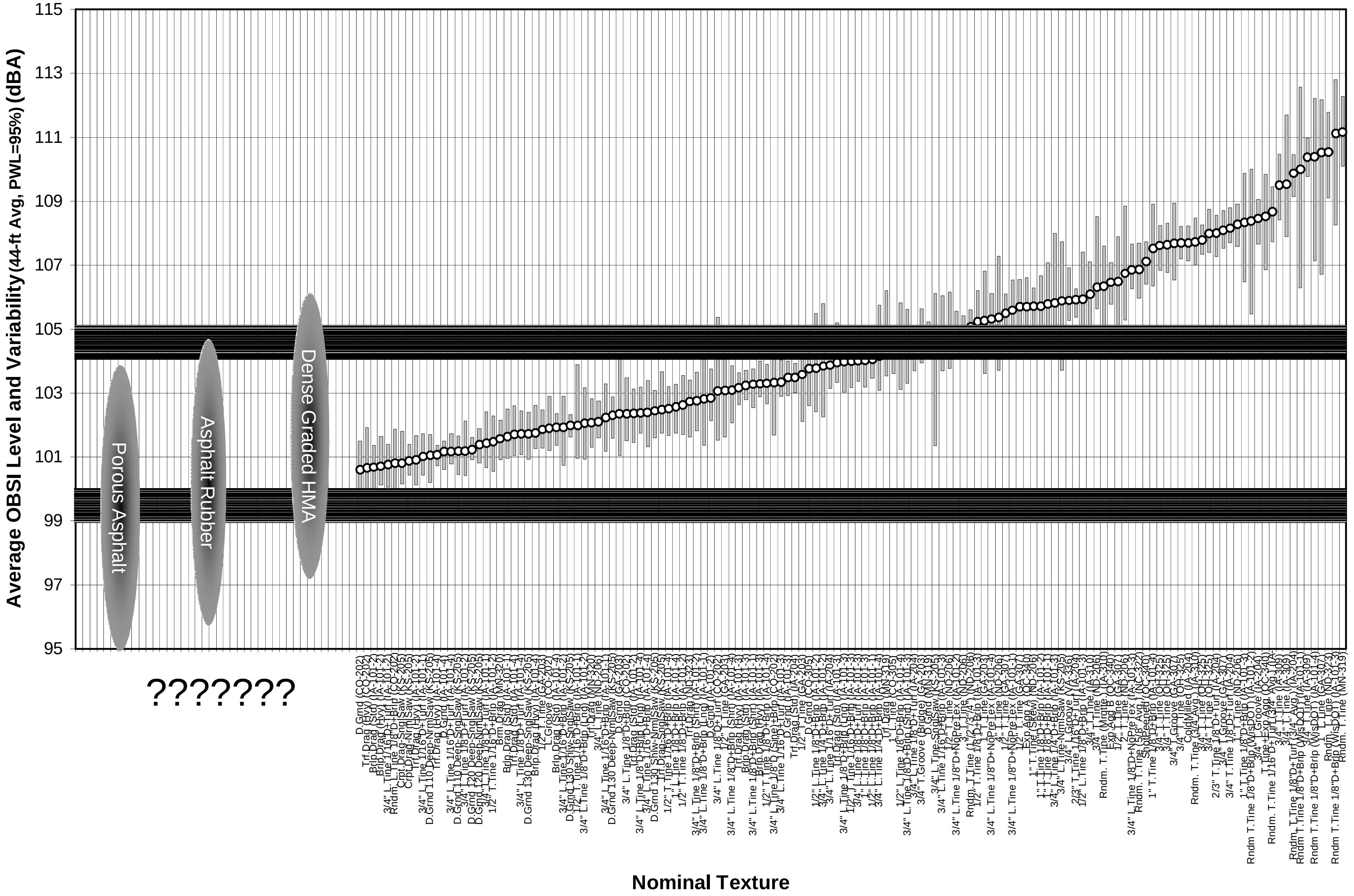

Figure 5.12. OBSI levels of nominal concrete pavement textures alongside some asphalt surfaces

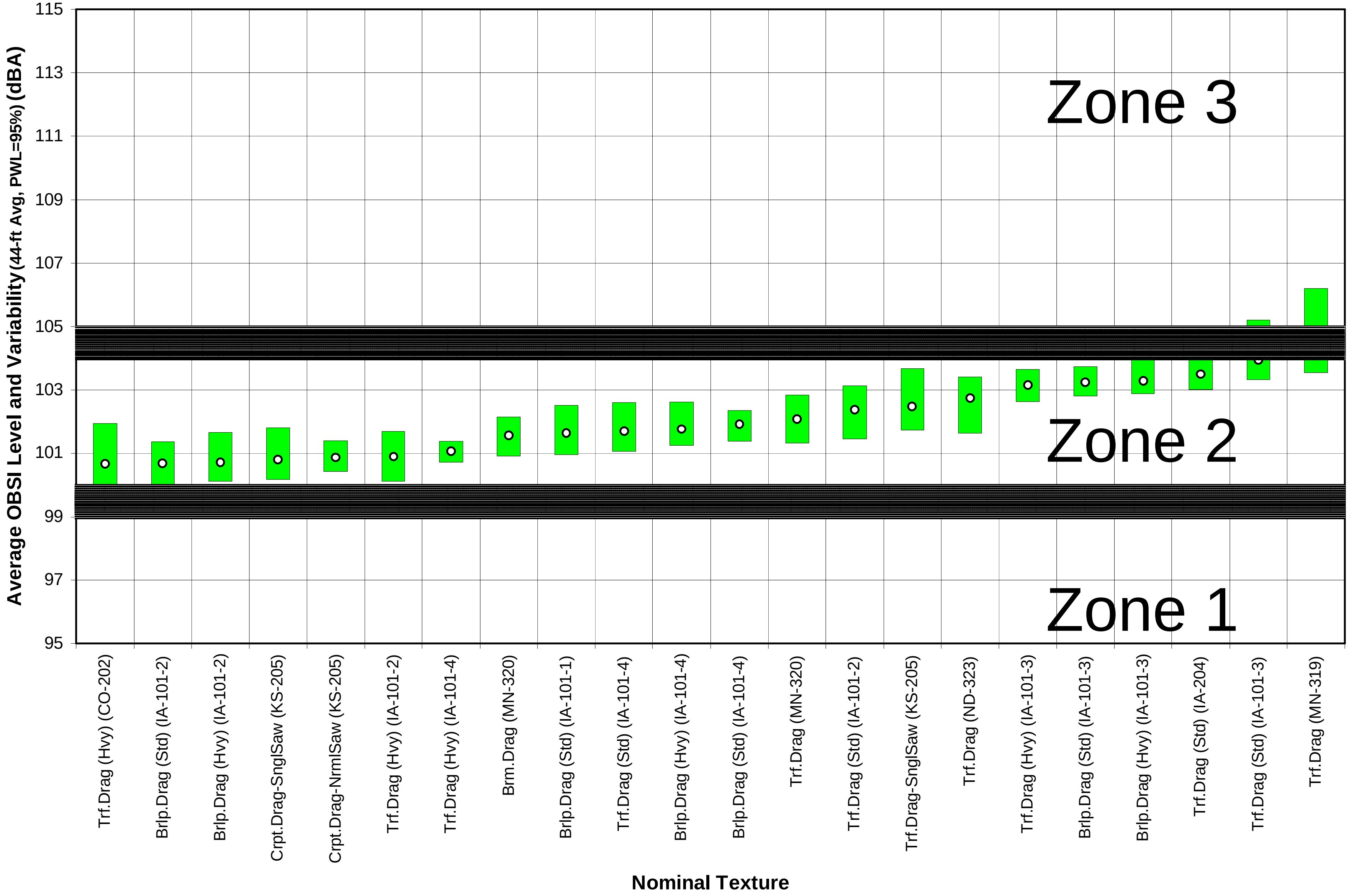

Figure 5.13. Average OBSI levels measured on drag texture sections

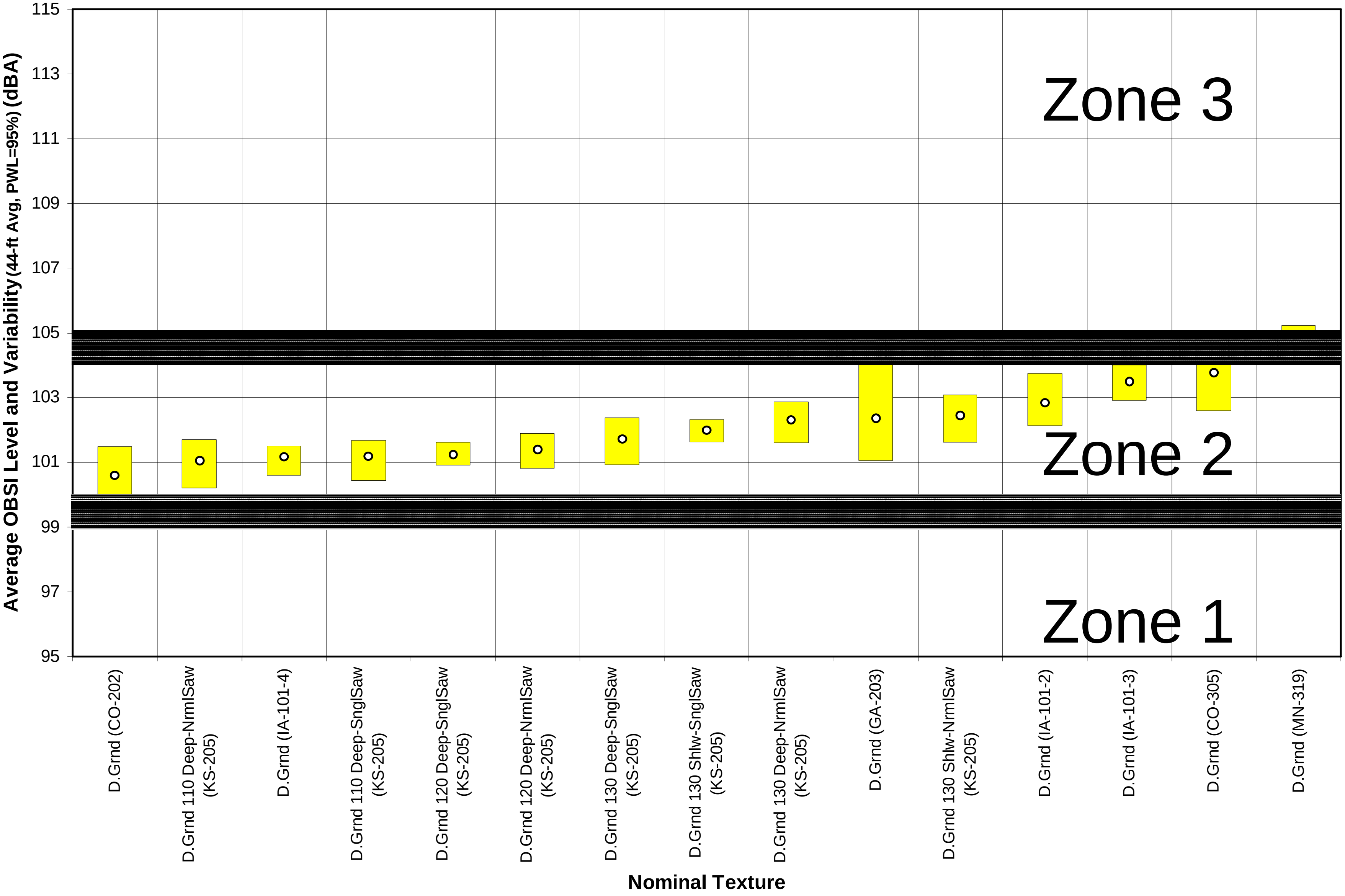

Figure 5.14. Average OBSI levels measured on diamond ground sections

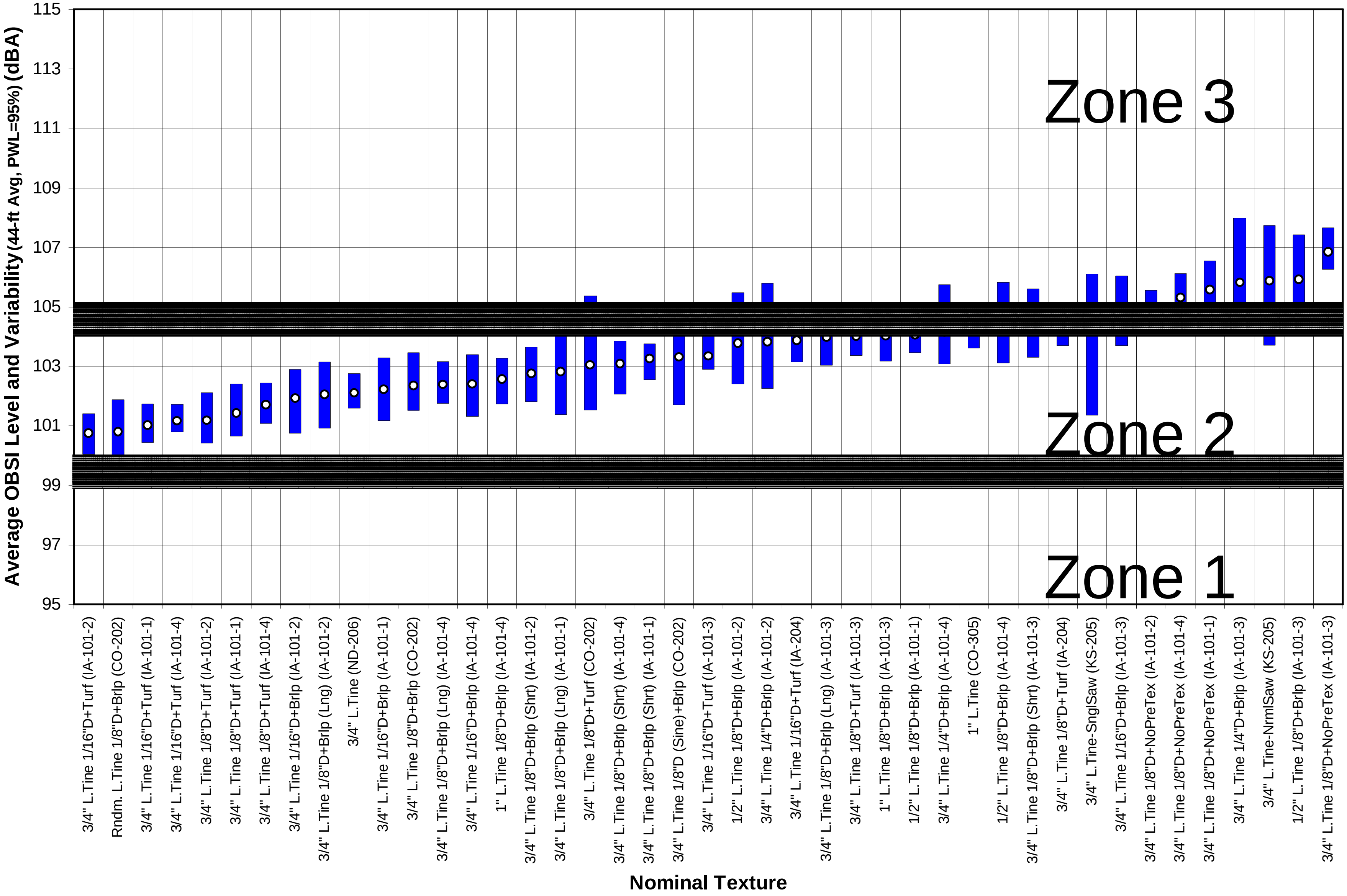

Figure 5.15. Average OBSI levels measured on longitudinally tined sections

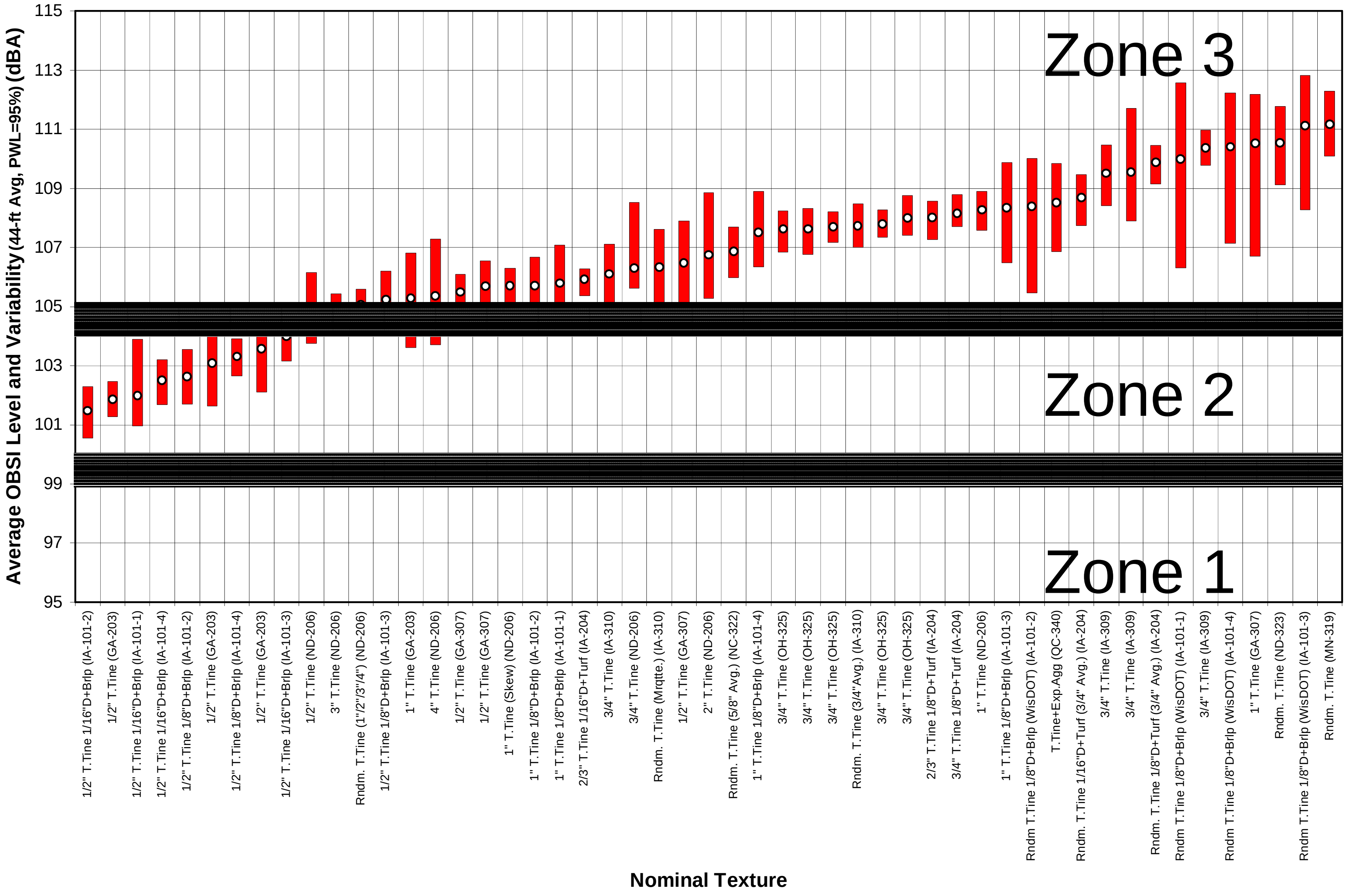

Figure 5.16. Average OBSI levels measured on transversely tined sections

This appendix provides an overview of basic knowledge and measurement practices associated with concrete pavement texture, noise, friction and smoothness. This information was gathered in the process of developing the *Strategic Plan for Improved Concrete Pavement Surface Characteristics* and *Evaluation of U.S. and European Concrete Pavement Noise Reduction Methods* (Part 1 of the ISU-FHWA-ACPA Concrete Pavement Surface Characteristics). This information represents fundamental principles as understood in existing literature and current practice. As such, this appendix does not focus on innovative measurement techniques or recent advancements in understanding these important surface characteristics.

A.1. TEXTURE BASICS

Pavement surface texture is also not a simple property to describe. To understand it, one must first recognize that it can be either anisotropic and directional (e.g., tining) or isotropic and more random (e.g., aggregate surfaces). It should be noted, however, that the latter is not truly random, since the aggregate gradation will lead to some degree of pattern development on the pavement surface.

Pavement surface profile characteristics can be broken into four ranges (Ayton 1991): (1) unevenness/roughness, (2) megatexture, (3) macrotexture, and (4) microtexture. See Figure 2.1 (CROW 2003).

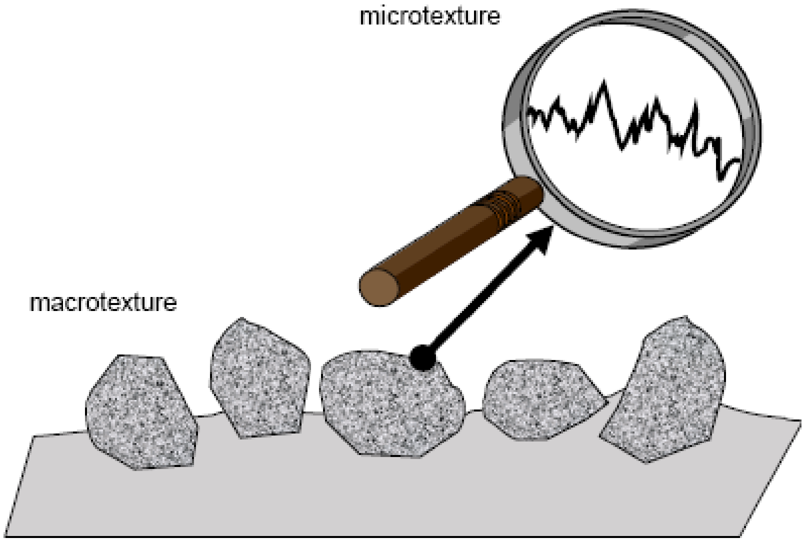

Figure A.1. Pavement surface texture categories of macrotexture and microtexture

The wavelength of texture is defined as the spacing between the crests of sequential (repeating) surface features. In pavements, multiple texture wavelengths occur simultaneously, which means that the tire and the pavement interact in a complex manner. A series of international standards, ISO 13473, describe how texture can be measured and characterized (ISO 1997).

Figure A.2 illustrates the ways texture classifications are sometimes reported and the pavement surface characteristics that are commonly associated. Within these four categories, the wavelength range of interest for smoothness, friction resistance, and noise interact with each other. For example, avoiding roughness helps enhance ride quality, but roughness increases road-holding ability, which may boost safety. While megatexture is known to increase noise, macrotexture is thought to help decrease it. In addition, macrotexture helps provide drainage for increased safety. Further, microtexture is desirable because it provides adhesion, which is necessary for friction resistance. However, excessive adhesion may also increase noise.

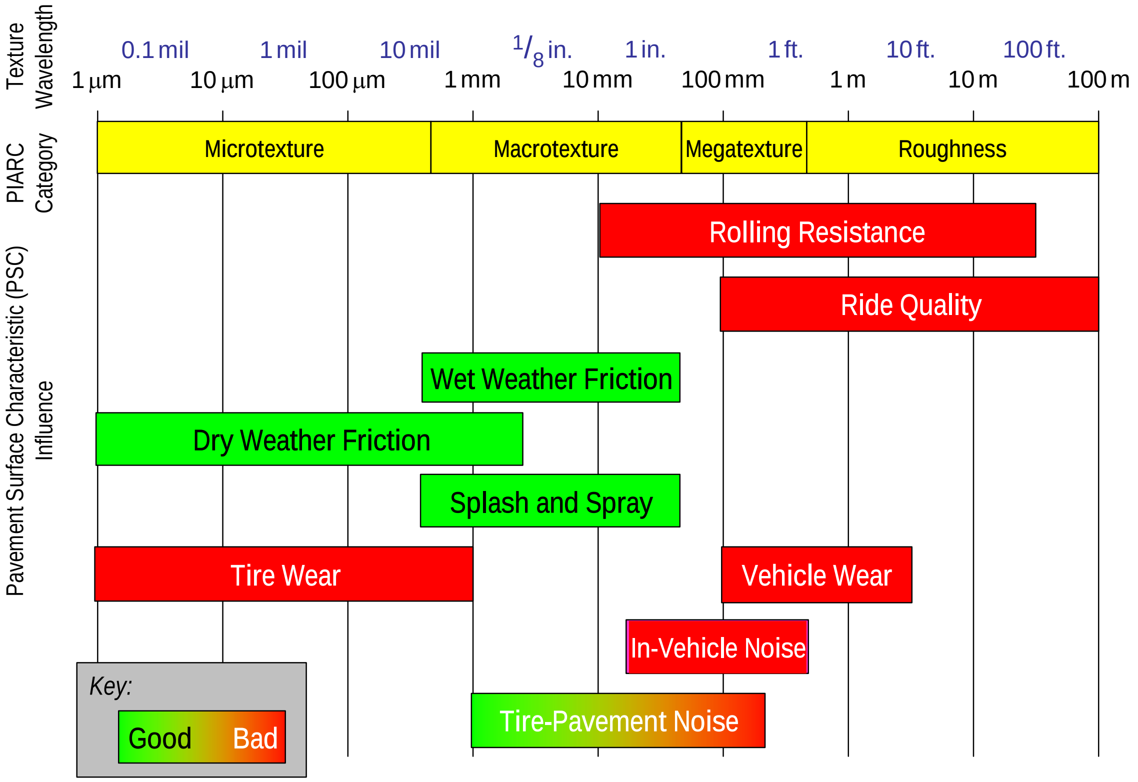

Figure A.2. Relationship of pavement surface texture to various characteristics

Roughness (sometimes termed “unevenness”) is technically its own classification of texture, with long wavelengths of 500 mm (20 in.) or more. Megatexture is defined by wavelength values ranging from 50 to 500 mm (2 to 20 in.). (PIARC 1987). Variations in texture at this level usually result from poor construction practices, surface deterioration, or local settlements.

Macrotexture is an important category of texture, with wavelength values falling between 0.5 and 50 mm (0.02 and 2.0 in.) (PIARC 1987). On pavement surfaces, macrotexture can be produced by grooving, indenting, or otherwise forming small surface channels in the pavement surface. Most aggregates used in concrete pavements also fall within this range. Therefore, texture in this wavelength category occurs if the aggregates are exposed. Macrotexture is important because it is not only a primary contributor to pavement noise but is also a factor in many other pavement surface characteristics, including friction and splash and spray (Ergun et al. 2004; Nelson et al. 2003; Sandberg 1998). Average depths of macrotexture are currently measured through the use of high-resolution lasers (see ISO 13473 or ASTM E 1845) or by use of the sand patch method (see ISO 10844 or ASTM E 965) (ISO 2004; ASTM 2002; ISO 1994; Hardtl 2004).

Microtexture consists of the irregularities not readily visible to the naked eye. This includes texture from fine sands and the surface roughness on the aggregate particles themselves. Wavelengths in this category are less than 0.5 mm (0.02 in.) (PIARC 1987). Texture at this level does not significantly contribute to tire-pavement noise at highway speeds, but does influence other surface characteristics, such as pavement friction (Nelson et al. 2003).

A.2. NOISE BASICS

Noise and Sound

Noise is unwanted sound. As such, noise is a subjective quantity. The level of noise depends on the extent to which the sound is unwanted, as opposed to a physical level. Some of the confusion lies in the interchangeability of these terms. While our industry will likely continue to cite "noise" where the term "sound" would be more appropriate, it is important to recognize that they are technically different.

Sound is composed of small air pressure fluctuations. These pressures are quantified using decibel (dB), a logarithmic ratio of the acoustical pressure fluctuation compared to a reference pressure fluctuation (typical of the lowest threshold of hearing).

A-weighted sound pressure levels are often expressed as dBA. While the use of A-weighted sound pressure level does not capture all of the annoyance characteristics of sound, it is an adjusted (weighted) measure that models the physiological sensitivity of the human ear to various frequencies of sound. It should be noted that while other factors such as the sharpness, roughness, and tonality of sound are important to annoyance, they are not captured by dBA (Zwicker and Fastl 1999). In addition, it should be noted that an increase of 10 dBA may be perceived as a doubling of noise.

Sources of Traffic Noise

Two major sources contribute to noise observed at the roadside: powertrain noise and tire-pavement noise. Powertrain noise is attributed primarily to engine noise and exhaust emissions. Tire-pavement noise is attributed primarily to the interaction of the tire and pavement, but also includes vehicle vibration and aerodynamic noise. The noise caused by the interaction of tire and pavement is considered dominant at high speeds, but it is overshadowed by the engine and exhaust at low speeds. The crossover speed between these two sources depends on the type of vehicle, pavement texture, traffic conditions, and several other factors (Hibbs 1996). As such, there is not complete agreement in the literature about the speed at which tire-pavement noise becomes the dominant source. However, there is agreement that at highway speed tire-pavement noise is dominant (Sandberg 2002).

For dry pavement, Sandberg (2002) attributes tire-pavement noise to three fundamental mechanisms: (1) tire radial vibrations, (2) tire tangential vibrations, and (3) air pumping. Radial vibrations happen when the tread impacts the road, which causes side wall vibrations. This mechanism is exacerbated by road roughness. Tangential vibrations are caused by sliding motion within the tire contact patch, or by the vibration that results from the tread sticking to the pavement and then being quickly released. Air pumping causes shock waves that propagate as sound when the air that is trapped between the tire and the road makes rapid transitions from compression to expansion.

Each of the three noise mechanisms described above are caused by surface texture in a distinct range of wavelengths (Nilsson 1980). As such, they cause noise in a distinct frequency range. This relationship is very sensitive to vehicle speed. Macrotexture and microtexture cause vibrations within the tread of a tire. Macrotexture also decreases pavement noise because it mitigates the air pumping effect by helping to prevent air from getting trapped. Megatexture causes tire vibration beyond the contact patch, such as vibrations of the side wall. These complicated relationships between pavement surface characteristics and noise have thus far prevented the direct specification of pavement surface texture. However, some relationship between texture power spectra and sound power spectra have been reported (Eberhardt 1985). In some cases, this relationship may be irrelevant because noise abatement should not be achieved at the expense of safety.

Tire tread design is thought to have much less influence on traffic noise than the road itself. For tire vibration effects, this is because the functional aspects of tire design prevent them from having much diversity in tread or side wall stiffness that may lead to major changes in the potential for producing noise. On the other hand, tire tread design affects the air pumping mechanism significantly (Ejsmont 1984; Willett 1975). A “good” tread design is one that allows air to escape as the tread makes contact with the road. This mechanism is responsible for the findings of some studies in which the relative noise levels on various pavement types did not produce the same rankings for different tire tread designs (NBS 1970).

With respect to pavements, noise is dependent on both acoustic absorption (also cited as “absorption”) and surface texture. For pavements, absorption is beneficial because it reduces both the noise generation at the tire-pavement interface as well as noise otherwise reflected off the pavement (Sandberg and Ejsmont 2002). The size and shape of surface texture also controls sound generation at the tire-pavement interface. Tire-pavement noise generation is also roughly proportional to speed and is more prevalent for vehicles traveling at highway speeds (Hultqvist and Carlsson 2004). As a result, while some pavements may mitigate noise at low speeds, the benefit is often most pronounced for high-speed thoroughfares.

Absorption describes the amount of sound energy that is absorbed (as opposed to reflected) by a material. It is expressed as a fraction of the energy that is absorbed, defined as the energy absorption coefficient (α), a value from zero to one. A value of α near zero occurs for an acoustically hard surface, where most of the sound is reflected. Conversely, a value of α near one indicates an acoustically soft material, where most of the sound is absorbed. Absorption is not always easy to understand and is often difficult to measure. It is a function of a number of factors, including the frequency of sound and the angle at which sound waves approach a surface.

Acoustical absorption is closely linked to porosity and permeability, and both fundamental and empirical relationships have been derived to describe these phenomena. In simple terms, all else being equal, the more pervious and permeable a material is (to air), the higher the acoustical absorption will be. Striving for higher absorption materials is an important target for the pavements industry. Materials with higher absorption have the benefit of not only reducing noise at the tire-pavement contact area, but also reducing other noise generated by other vehicle sources (e.g., powertrain).

Noise Measurement

Noise is directly quantified by the root mean square of sound pressure fluctuations traveling through the air. However, this quantity is rarely used to describe noise level. Instead, noise level is reported as sound pressure level in decibels (dB). This is done by normalizing the mean square pressure level by a reference value and computing the logarithm of the result. The dB scale is very convenient because it is anchored at a value of 0 for the typical threshold of human detection. Unlike direct measurements of sound pressure fluctuations, it does not span several orders of magnitude.

Note that the dB scale is not additive, such that a doubling of the sound energy increases the noise by 3 dB. On this scale, a value of 35 dB may be typical of a quiet library, while a value 130 dB is at the threshold of pain. Although this scale is meant to reflect a human’s physiological response to sound, different people react to sound differently.

Raw measurements of sound pressure level do not reflect typical human reactions to sound. The human ear can detect frequencies from 20 Hz to about 20,000 Hz and are most sensitive to the range from 1,000 Hz through about 5,000 Hz. To account for this, standard frequency weightings are applied to sound pressure measurements before they are summarized by a dB value. For moderate sound levels, a standard frequency weighting, called the A-weighting, is applied before the final sound pressure level is calculated. The resulting value is expressed as dBA. This is the most common scale for reporting traffic noise.

On the dBA scale, noise may be reported in several ways. All of these values are given the symbol L to distinguish them from direct measurements of sound pressure fluctuation:

L_{eq}: This is the equivalent sound pressure level. It represents a single sound level that would be needed to equal the average influence of a varying sound level over a given period of time.

L_{10}: This is a statistical description of sound level. It is the threshold sound level that was exceeded for 10% of the overall time of the measurement. L_{10} is a common descriptor of peak traffic noise levels with significant but sparse events. Other percentiles have also been used.

L_{max}: This is the maximum noise level observed for a very short period of time over a given measurement interval.

For residential areas, U.S. noise regulations specify that receivers with values that approach 67 dBA L_{eq} be considered for noise abatement (FHWA 1995).

Traditionally, traffic noise has been measured at the roadside as a random sampling of vehicles passes by. This method provides a direct estimate of the sound level that has propagated to the roadside because of a given vehicle or traffic mix. The pass-by method captures the sound produced at the tire-road interface and the effects of the pavement surface on sound propagation. However, the sound level measured using the pass-by method includes the noise from all sources, including powertrain noise. Thus, although the pass-by method provides an estimate of the annoyance that traffic noise may cause to nearby residents, it requires careful control of multiple variables (microphone placement, air temperature, ambient noise, etc.) when it is used to compare vehicle and road surface combinations.

An alternative means of noise measurement that has become more common in recent years are source or near-field methods (ISO 1997). This includes both close-proximity (CPX) techniques as well as on-board sound intensity (OBSI) methods. In these measurements, microphones are mounted to a vehicle near the contact patch. This seeks to isolate the noise at the contact patch from other sources. For this reason, it may provide a more direct comparison of the effect of tire type and road surface texture on noise generation. Although it isolates the noise caused by tire and pavement contact from other sources, it ignores the effects of noise propagation (Donovan 2003). Thus, these methods do not provide a complete assessment of pavement type. Nevertheless, near-field measurements of noise have become a very useful research tool.

Since the pass-by method and near-field methods do not measure the same set of noise sources, there is no perfect relationship between them. Indeed, recent studies have found that these methods may rank the noise level of a given set of pavements differently with each method (LaForce 2001; Mn/DOT 1987; North Dakota DOT 1994; McNerney et al. 2000).

Either method, like any measurement, has inherent shortcomings. Much of the research done on traffic noise in the past three decades has reported on the sensitivity of noise measurement to different variables. Each of these must be controlled carefully if measurements from different studies are to be compared directly. For example, von Meier (1990) observed a difference of up to 6 dBA between different tire types on the same roads at a standard speed. Perhaps more importantly, the quietest road was not the same for each tire. Vehicle speed, vehicle type, pavement surface temperature, and air temperature also strongly affect traffic noise. In addition, the manner in which the measurement is made is very important. Efforts are underway by the FHWA, ISO, and others to standardize every aspect of measurement methods.

A.3. FRICTION BASICS

Tires and Pavement Friction

The amount of retarding force that a tire can develop at the pavement interface is directly related to the level of slip. During braking, slip is defined as the difference, in percent, between the vehicle forward velocity and the velocity implied by the tire rotation. Thus,

$$\text{Slip} = 100 \bullet (V_X - R \bullet \omega)/V_X$$

where V_X is the vehicle forward velocity, R is the tire-rolling radius, and ω is the rate of tire rotation (van Eldik Thieme 1971). During free rolling, the value of slip is 0. When the brakes are applied, the wheel rotational speed decreases more rapidly than the vehicle velocity, and slip takes on a positive value. If the wheel is locked (i.e., not rotating) the tire is sliding, and the value of slip is 100.

The longitudinal force developed at the interface between the pavement and the tire depends very heavily on the level of slip. Figure 2.3 shows a sample measurement of the longitudinal force on a rolling truck tire versus slip for wet and dry pavement (Ervin 1981). The longitudinal force is normalized by vertical load to help estimate the level of deceleration that can be achieved at each level of slip. The values on the vertical axis are usually interpreted as a dynamic coefficient of friction.

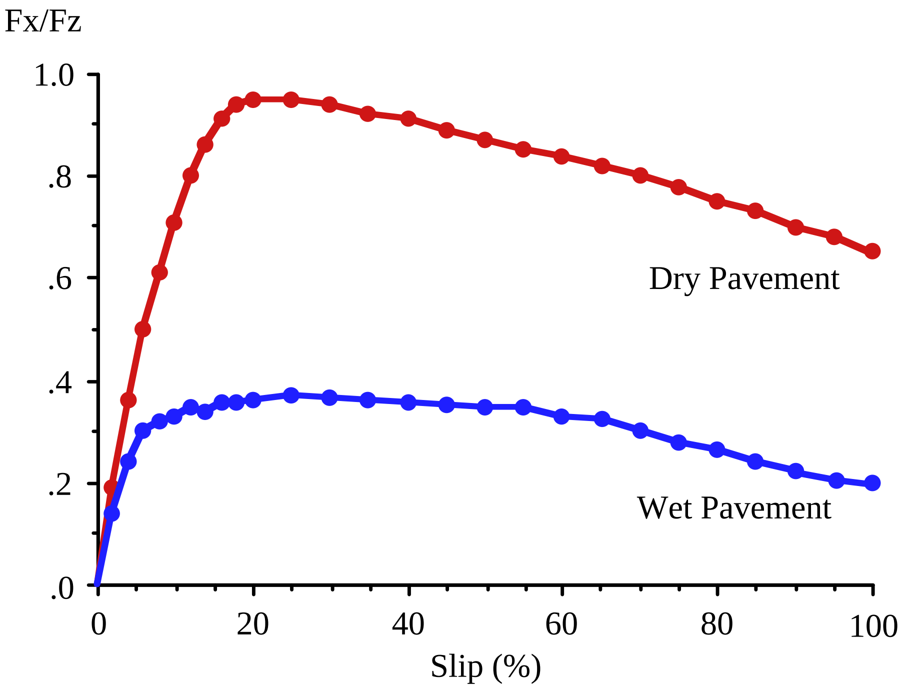

Figure A.3. Longitudinal force versus slip

Figure A.3 provides an example of several important aspects of the way vehicles use pavement friction. First, the peak level of friction for operation on both wet and dry pavements occurs for a slip of about 20%. For most tire and pavement combinations, the peak will occur between 5% and 30% (Kummer 1966). Second, the coefficient of friction is reduced significantly when the wheel is locked up (at 100% slip). This is the sliding friction value (Meyer 1962). The reduction in friction for the locked-wheel case is also common. This is the motivation behind anti-lock braking systems, which attempt to maintain a level of slip near 10% to optimize the friction level. Third, the friction level on wet pavement is much lower than that on dry pavements, regardless of the wheel slip (Dijks 1974). For this reason, wet pavement friction is considered paramount to pavement safety. In fact, surveys of friction for the purposes of evaluating pavement sufficiency rarely consider dry pavement friction and have assigned the term “friction resistance” to the level of wet pavement friction at 100% slip.

Note that Figure A.3 shows the friction level for a tire that is not cornering. When a tire is also providing lateral force to a vehicle, the maximum level of longitudinal force that it can provide is reduced. When a tire is operating near its lateral force (handling) limit, it can provide almost no longitudinal force (braking) (Bernard 1977).

At a low level of slip, most of the longitudinal force is transmitted to the tire by adhesion to the pavement surface. Potential for adhesion is provided primarily by microtexture. At a high slip speed, sufficient macrotexture also becomes important. This is because the tire tread elements will deform as they pass over coarse macrotexture. This mechanism dissipates energy.

Friction Measurement

Henry (2000) reported that four basic types of in situ friction measuring devices are in common use: (1) locked wheel, (2) fixed slip, (3) variable slip, and (4) side force. In a survey, Henry found that the majority of U.S. highway agencies were using an ASTM E 274 trailer to measure friction, which is a locked wheel friction-measuring device.

Locked wheel friction devices measure wet pavement friction at 100% slip and are typically mounted on a trailer. The trailer supplies a small film of water, and the longitudinal force is measured over a short duration while the wheel is locked. This type of trailer is commonly used with one of the two standard test tires: ribbed or smooth. Unfortunately, these two tires may rank the friction resistance of roads differently. This is because the ribbed tire provides large channels for the water film to escape, whereas the smooth tire does not. This makes the ribbed tire insensitive to macrotexture, which is usually needed to provide the drainage (Henry 1983a). Although the ribbed tire provides a good estimate of the sufficiency of pavement microtexture, it may report a friction resistance value that is artificially high on a pavement with insufficient drainage. Therefore, the net effect of using a ribbed tire to survey a pavement network is to put pavements with good drainage at a disadvantage.

Fixed slip friction testers operate at a constant slip in an attempt to measure the peak wet friction level. This value usually falls between 10% and 20%. As in locked-wheel testers, fixed slip testers are usually mounted on a trailer that supplies a film of water to the tire and measures the longitudinal force during an event in which the required level of slip is induced. Variable slip devices are very similar to fixed slip devices, except that they sweep through a range of slip values. Variable slip testers provide an entire friction versus slip characteristic, such as that shown in Figure A.3. Many of the locked wheel testers in operation around the United States have the ability to operate in a variable slip mode but are usually used as locked-wheel testers to comply with ASTM E 274.

Side force friction testers are not common in the United States. They measure the cornering force that exists while the tire is held at a fixed yaw angle but allowed to roll freely. Because of their configuration, side force testers generally measure friction at a low slip condition.

International Friction Index

The locked wheel friction resistance measurement described above has become a common aspect of road network monitoring in the United States (Henry 2000). However, locked wheel measurements are most sensitive to pavement microtexture, particularly if a ribbed tire is used. As such, they are able to verify that a pavement has adequate adhesion, but ignore the contribution macrotexture may make to drainage. Recent efforts by PIARC have sought to remedy this situation through the development of the International Friction Index (IFI) (PIARC 1995). The IFI is a composite index that captures the influence of microtexture and macrotexture into a single value.

The contribution of microtexture may be measured using a trailer-mounted friction tester, as described above, or a device called a dynamic friction tester (DFT). The DFT is a small device that is placed on a pavement and observes the ability of a pavement to slow a spinning flywheel through wet contact with small rubber feet.

The contribution of macrotexture is included through direct measurement of the texture level. This is usually done using the circular track (texture) meter (CTM) (Henry et al. 2000). The CTM measures the profile of the pavement in a circle that is ten inches in diameter. The measurement is used to calculate mean profile depth (MPD). Several other methods, such as the sand patch test and Road Surface Analyzer (ROSAN), have also been used to estimate macrotexture.

After completing a rather ambitious testing program and performing detailed statistical correlation, PIARC was able to harmonize estimates of pavement friction from common measurement schemes. The result of this work is a method of combining the contribution of microtexture and macrotexture to form the IFI, regardless of the measurement source. Since the original experiment in 1992, an ongoing effort maintains a database of correlations between friction measurements through the annual friction workshop in Wallops Island, Virginia.

A.4. SMOOTHNESS BASICS

Incentives for Smoothness

To help provide smooth pavements, most state DOTs have implemented smoothness specifications, in which incentive payments are available for very smooth pavements and penalties are imposed for unacceptably rough pavements.

Profilograph Index

Most of the states with smoothness incentive programs originally used the profilograph for measuring smoothness. A profilograph is a rigid frame with support wheels at both ends and a center wheel. The support wheels at the ends establish a datum from which the deviations of the center wheel can be compared. The movement of the center wheel is recorded, and the trace is reduced to a single value that serves as an estimate of smoothness. The smoothness value is called the profilograph index (PI). The PI is the sum of the heights of all of the scallops that appear in the profilograph’s trace. A scallop is defined as a protrusion of the profilograph’s trace beyond a given limit. Each time this limit is violated, a contribution to PI is added that equals the height of the protrusion. Typically, the threshold limit is 0.1 inches in either direction (i.e., a 0.2-inch blanking band) (Scofield 1992; Kulakowski 1989). If a pavement feature produces a very large scallop, corrective action is required.

Note that with a threshold level on profilograph response of +/- 0.1 inches it was common to produce a pavement with no scallops. This led to anecdotes in which pavements with roughness that was annoying to the public achieved a perfect smoothness score. This was possible because low-amplitude roughness with quick reversals could still be annoying because it would cause axle hop in vehicles (Gillespie 1992b). This type of feature has the nickname “chatter” and prompted the elimination of the threshold value (i.e., a zero band). Without the threshold value, every dump and dip is considered a scallop, with some rules applied for eliminating insignificant features. Even with this improvement, profilographs have little direct relevance to vehicle response. First, they are very sensitive to features that are the same length as the wheelbase of the device (Gillespie 1992a). The most common type of profilograph, the California profilograph, has a wheelbase of 25 feet. Second, the method of counting scallops creates a system in which a pavement that is simultaneously wavy and contains chatter would be rated better than a pavement with chatter only (Karamihas 2004b).

International Roughness Index

Weaknesses in the profilograph and the pervasiveness of inertial profilers for use in network pavement management have prompted a move to the International Roughness Index (IRI) for construction quality control. The IRI is calculated from a longitudinal profile measurement, typically from an inertial profiler. For measurement of new construction, lightweight profilers are most commonly used, which are inertial profilers mounted to a small all-terrain vehicle.

An IRI was developed in the 1980s when the World Bank initiated a correlation experiment in Brazil to establish a correlation and a calibration standard for existing roughness measurement devices (Sayers et al. 1986). These devices measured road roughness through direct measurements of their host vehicle response, but were mounted to a diverse group of host vehicles. The IRI, on the other hand, was calculated from a measurement of profile, and therefore had a consistent meaning. Thus, if the profile were measured properly, it could serve as a correlation standard for other roughness measurement schemes (Gillespie 1980). It was also tuned to be as relevant as possible to as many vehicles as possible (Sayers 1998). It has since been shown to provide good information about several aspects of vehicle response, including general pavement condition, truck dynamic loading, automobile ride quality, and truck ride quality (Gillespie 1992a).

Since its development, the IRI has become the standard roughness index for network pavement management. The FHWA has required the states to report the roughness of their Highway Performance Monitoring System (HPMS) sections in IRI. Most states are also using IRI as the parameter for monitoring the roughness of their highway network. As profilers begin to replace profilographs for measuring new pavement smoothness, it appears that the IRI will eventually become the dominant measure of new pavement smoothness.

Readers who need more background on inertial profilers and the IRI are referred to *The Little Book of Profiling* (Sayers 1998).

AASHTO Smoothness Standards

Four AASHTO provisional standards exist for implementing pavement smoothness specifications:

- AASHTO MP 11-03. Standard Specification for an Inertial Profiler
- AASHTO PP 49-03. Standard Practice for Certification of Inertial Profiling Systems
- AASHTO PP 50-03. Standard Practice for Operating Inertial Profilers and Evaluating Pavement Profiles
- AASHTO PP 51-03. Standard Practice for Pavement Ride Quality Specification when using Inertial Profiling Systems

Together, these standards provide the framework for a smoothness quality assurance program. The standards recommend the use of inertial profilers measuring pavement smoothness and base incentive and disincentive payments for smoothness on the IRI.

The standards cover most of the elements needed to implement a smoothness quality assurance program. Standard MP 11-03 specifies all of the components needed in an inertial profiler, including hardware, software, and operational requirements. It is meant to assist an agency or contractor in the development of the equipment procurement specification. Standard PP 49-03 defines a profiler certification program. The standard recommends that an inertial profiler be certified before it is used within a quality assurance program. Certification is obtained by demonstrating that profile and IRI measurements are repeatable and agree with reference measurements on a limited number of sites. PP 50-03 describes the way a profiler should be operated, calibrated, and periodically subjected to “sanity checks.” The standard also suggests a file format for road profiles. PP 51-03 defines an incentive and disincentive program that is based on the IRI. It proposes bonus and penalty schedules, sets limits for corrective action, and provides a method for detection of localized roughness.

The purpose and makeup of the standards have been very carefully considered. The methods they recommend are the best that were available when the standards were written. In addition, the numerical values and thresholds set for many of the engineering aspects of the standards are based on the best information that was available. Some parts of the standards specify performance and leave the methods up to the practitioner and others specify the method for obtaining the desired performance. As the field becomes more advanced, the specifications will evolve to require performance only.

These standards provide an excellent resource for implementing a smoothness quality assurance program, but they should be under constant review as more is learned about the measurement and interpretation of pavement smoothness. All of the methods and settings that appear within the specifications have real consequences in the field. It is up to the research community to develop an understanding of how each part of these specifications affects their end goal: smooth pavement. Each aspect of the standards should help promote pavement smoothness in some way. Furthermore, each method and setting must be the result of rational science and engineering that can be defended by quality research and must be demonstrated to be realistic and practical for use in the field.

Profile Measurement

Accurate and repeatable measurement of profile is essential to the success of a smoothness incentive program. No matter the index used to rate smoothness, including the IRI, simulated PI, or some index that has not yet been proposed, the ability of the construction industry to minimize roughness depends on the quality of profiler output. Measurement problems currently hinder this effort (Karamihas 2003; Karamihas 2004a). Initiatives are underway to improve the state of the art in smoothness measurement.

B.1 SPECIFICATIONS FOR THE DESIGN AND CONSTRUCTION OF EXPOSED AGGREGATE CONCRETE PAVEMENTS IN THE UNITED STATES

1. General

1.1. Introduction to Exposed Aggregate Concrete Pavement

1.1.1. Exposed aggregate concrete pavement, sometimes referred to as "whisper concrete," has been demonstrated to be a long-life option with lower traffic noise than conventionally textured roads while offering comparable skid resistance. The exposed aggregate texture forms a matrix of interconnected paths below the surface through which water can pass, thus maintaining adequate skid resistance while assisting in the reduction of tire-pavement noise. Furthermore, there may be a slight reduction in spray generated by high-speed vehicles.

1.1.2. While the level of noise emitted at the tire-pavement interface on exposed aggregate concrete pavements is generally higher than that of pervious surfaces, it is lower than most dense surfaces, including hot-mix asphalt, conventionally textured concrete pavements, and most surface treatments. Exposed aggregate concrete pavement also offers comparable skid resistance to each of these alternatives.

1.1.3. In addition, exposed aggregate concrete pavement is perceived to have better tonal qualities than conventionally textured concrete surfaces, especially when compared to transversely tined surfaces.

1.1.4. The use of exposed aggregate concrete pavement is dependent upon "wet-on-wet" or two-layer construction. There are potential cost savings in the process by using lower quality materials on the bottom layer. This in turn will help offset the costs of the top layer and the associated work involved in exposing the surface.

1.1.5. The appearance of exposed aggregate is similar to that of a similar technique employed in architectural applications, with a surface that derives its color from the exposed aggregates.

1.2. Scope of Specification

1.2.1. This document outlines the use of exposed aggregate concrete pavements, sometimes referred to as "whisper concrete." It includes guidance and commentary on the design, specification, construction, and life of this pavement type. It is not intended to serve as a stand-alone document. Instead, it should supplement guidelines and specifications for conventional concrete pavements as appropriate.

1.2.2. The scope of this document is to provide the necessary materials and procedural information required to design and construct an exposed aggregate concrete pavement.

1.3. Exposed Aggregate Concrete Pavement Development

1.3.1. Exposed aggregate concrete pavement was first used in Denmark and was subsequently developed in Belgium with the goal of producing a safe, long-life concrete pavement as an alternative to the conventionally textured concrete used previously. The technique has been successfully used since the 1970s and is now the typical texture used on concrete pavements in Belgium and elsewhere.

1.3.2. In the late 1980s, the environmental problem of tire-pavement noise was raised in Austria. With the objective of identifying a low-noise concrete pavement that would stand up to studded tire wear, the Austrians refined the Belgian process, discovering that, by reducing the size of the aggregates in the coarse aggregate fraction, the tire-pavement noise levels could be substantially reduced. Most exposed aggregate concrete pavements are constructed in two lifts, with a lower lift meeting minimal standards and an upper lift consisting of high-quality, durable concrete. Consideration was given in Austria to full-depth construction as an alternative to this. This proposal was later rejected, however, since it would have used large quantities of premium aggregate.

1.3.3. Two-course construction, the normal form of exposed aggregate concrete pavement construction in Austria, provides an economic, long-lasting surface that results in a measurable noise reduction when compared with conventionally textured concrete pavements. Other countries that have used exposed aggregate concrete pavements include France, the Netherlands, Australia, and some trial projects in the United States.

1.3.4. In Sweden, exposed aggregate concrete pavement has provided a durable surface that has been able to withstand the punishing effects of studded tires during the winter months.

1.3.5. Exposed aggregate concrete pavement is also used in the United Kingdom. However, a larger aggregate is used than that used on the roads in Austria. A higher skid requirement is specified in the United Kingdom. It was found that in order to provide adequate low- and high-speed skidding resistance, a deeper texture depth and thus a larger aggregate size are required. While many European countries have used exposed aggregate concrete pavement techniques on jointed concrete pavements, the United Kingdom and Belgium use the technique on continuously reinforced concrete pavement (CRCP).

1.4. Key References

1.4.1. *Manual of Contract Document for Highway Works – Volume 1 Specification for Highway Works* (United Kingdom Highways Agency, May 2005)

1.5. Use

1.5.1. Exposed aggregate concrete pavement can be used in any location where a concrete pavement is proposed, including heavily trafficked roads.

1.6. Typical Characteristics

1.6.1. Durability

1.6.1.1. Structurally, concrete pavements are typically designed for an equivalent traffic of 20–50 years. However, the surface will often require restoration during this period for smoothness and/or skid resistance.

1.6.1.2. If proper methods are used in the selection and proportioning of materials, durability problems can often be avoided. In the United Kingdom and elsewhere, exposed aggregate concrete pavement has been able to endure winter cycles (and thus winter maintenance) without any sign of distress.

1.6.2. Noise

1.6.2.1. While exposed aggregate concrete pavement is designed to provide an adequate level of skid resistance, both at high and low speeds, it can also be designed as a lower-noise surface. Various researchers have identified the respective roles of various types of texture with respect to tire-pavement noise. On low-speed roads, microtexture (texture sizes < 0.5 mm), often dependant on the roughness or harshness of the aggregate, can be of prime importance.

1.6.2.2. On higher speed roads, macrotexture (sizes 0.5 to 50 mm) become more critical. This texture is created by exposing the aggregate, and thus the gradation of the aggregate becomes critical. Megatexture (texture that is 50 to 500 mm) is undesirable, as it can be a major cause of tire-pavement noise and noise inside the vehicle.

1.6.2.3. Megatexture can originate during the course of construction in the form of corrugations or other surface irregularities. This type of texture can be minimized through use of a transverse finishing screed in advance of a longitudinal oscillating float. The intent is to maintain the aggregate surface in as level a plane as possible. The result will be improved smoothness and noise reduction.

1.6.3. Structural Capacity

1.6.3.1. Exposed aggregate concrete pavement surfaces can be used on either jointed plain concrete pavements (JPCP) or CRCP. Their structural capacity is not compromised by the use of exposed aggregate surfaces, as long as care is taken to maintain the required strength and thickness.

1.6.3.2. If the “wet-on-wet” two-course process is used, additional care may be required to ensure that the bond between the layers is sound.

1.7. Quality

1.7.1. Codes and Standards

1.7.1.1. FHWA Technical Advisory T 5040.36 - Surface Texture for Asphalt and Concrete, June 2005

1.7.1.2. ASTM E 965 - Sand Patch Test

1.7.2. Trial Construction

1.7.2.1. Preliminary trials of exposed aggregate concrete pavement should be conducted to demonstrate that the materials and concrete proportions are satisfactory for producing the desired texture. This is particularly important if exposed aggregate concrete pavement construction is new to the contractor and/or agency.

1.7.2.2. Preliminary trial panels should be constructed off site and should incorporate design and construction techniques for the exposed aggregate concrete pavement that are similar to those specified for the project.

1.7.2.3. The engineer should specify the length, width, depth, and other necessary details of the preliminary trials.

1.7.2.4. The preliminary trials should enable the contractor to determine the required application rate of the retarder, the timing, and the amount of brushing required to achieve the specified texture.

1.7.2.5. The average macrotexture depth should be measured on the end product and should be 0.7 mm, as defined by FHWA Technical Advisory T 5040.36 - Surface Texture for Asphalt and Concrete.

1.7.2.6. Testing for the average macrotexture depth should be conducted per ASTM E 965 - Sand Patch Test.

2. Materials and Equipment

2.1. Concrete Materials

2.1.1. Portland Cement

2.1.1.1. The type of cement used in the concrete should be limited to Type I or I/II portland cement (per ASTM C 150).

2.1.1.2. The minimum cement content of the concrete should be (375 kg/m^3) and the maximum free water-cement ratio should be 0.40.

2.1.2. Aggregates

2.1.2.1. For a coarse aggregate gradation of 6.3/10 mm, the amount of coarse aggregate retained on the 10-mm sieve should not exceed 3% by mass. For a 4/8 mm gradation, the amount of coarse aggregate retained on the 8-mm sieve should not exceed 3% by mass. For these gradations, the aggregate passing the 6.3-mm sieve and 4-mm sieve, respectively, should not exceed 10% by mass.

2.1.2.2. The fine aggregate grading should comply with the 0/2 (FP) or 0/1 (FP) grading, except that not less than 99% of the mass of the material shall pass the 2-mm sieve.

2.1.2.3. The coarse aggregate should comprise at least 60% by mass of the oven-dry constituents of the concrete.

2.1.2.4. The polished stone value (PSV), aggregate abrasion value (AAV), hardness, and durability of the coarse aggregate should be verified by the engineer.

2.1.3. Water

2.1.3.1. Water must be clean and free from oil, dirt, debris, and chemicals.

2.2. Other Materials

2.2.1. Retarder

2.2.1.1. In order to obtain a suitable exposed aggregate surface, the primary goal should be the removal of the surface mortar from the top of the slab in a controlled fashion. This objective may be achieved by the application of suitable cement set retarder, which is sprayed onto the surface of the fresh concrete immediately after it has been leveled and finished. The retarded mortar should then be removed by wet or dry brushing, generally no sooner than when the surface concrete has reached a maturity of 16 hours at 20°C, or after a suitable interval determined by the trial construction process.

2.2.1.2. The composition and viscosity of the retarder shall be such that it can be spread at an adequate and uniform rate over the surface of the concrete slab to ensure adequate aggregate exposure during the subsequent brushing operation.

2.2.1.3. The retarder should contain a pigment in sufficient quantity to give an even uniform color after it has been sprayed onto the slab surface. The pigment should be fully degraded by exposure to ultraviolet light without leaving any residue that is detrimental to the surface of the concrete.

2.2.1.4. The chemical composition of the retarder and the curing compound should be such that they do not react adversely following the application of the curing compound to the exposed aggregate surface.

2.2.1.5. The engineer should be notified in advance of the type of retarder that the contractor intends to use.

2.3. Plant, Equipment, Machines and Tools

2.3.1. The oscillating longitudinal float is an integral part of the paving equipment, playing a vital role in ensuring that a smooth, flat slab is produced prior to the application of retarder.

2.3.2. Where the oscillating longitudinal float is part of a separate piece of equipment, it is essential that it stays in close proximity to the paving train so that it works on a plastic concrete surface.

3. Construction

3.1. Placing Concrete

3.1.1. General

3.1.1.1. The concrete slab can be placed in either a single layer or in two lifts. For the latter, the surface layer should be laid monolithically with the lower layer in a “wet-on-wet” process.

3.1.1.2. The concrete surface layer should be fed, spread, compacted, regulated, and finished using equipment with elements to obtain the required uniform distribution and bonded embedment of the selected aggregate in the finished pavement.

3.1.1.3. If two-course construction is used, the concrete should be compacted in such a manner that the base layer concrete is not drawn into the surface concrete and that the select aggregate in the surface layer is uniformly present in the pavement surface.

3.1.1.4. The surface should be compacted and shaped to line and level by a combination of either internal vibration and fixed conforming plate or vibrating conforming plate.

3.1.1.5. The final regulation of the surface layer should be provided by a transverse finishing screed in advance of a longitudinal oscillating float traveling across the slab before the application of a retarder.

3.2. Concrete Finishing and Curing

3.2.1. General

3.2.1.1. The exposure of the aggregate on the pavement surface is a two-stage process, including (1) retarding of the surface mortar and (2) brushing to expose the aggregate.

3.2.2. Retarder

3.2.2.1. Preparation

3.2.2.1.1. Before commencing work, the level of the spray bar, rate of delivery of the retarder from the nozzles of the spray bar, and the forward speed of the spraying machine should be adjusted to achieve the required rate of spread. Means should be provided, and steps should be taken, to avoid excess retarder flowing onto the surface of the slab.

3.2.2.1.2. Backup equipment shall be available on the site at all times for use in the event of a breakdown or malfunction.

3.2.2.2. Application

3.2.2.2.1. The retarder should be spread evenly on to the surface of the concrete as soon as practicable after the surface layer has been leveled and finished. This should be done using a spray bar covering the full width of the slab in a single pass.

3.2.2.2.2. To achieve the required uniformity, the spraying system should consist of a spray bar, provided with nozzles, mounted on a machine spanning the slab. Temporary works materials and equipment should be chosen to permit inspection and thus to ensure adequate coverage of the retarder immediately after spraying and before protection of the surface.

3.2.2.3. Protection of the Surface after Retarder Application

3.2.2.3.1. The finished surface of the concrete, after application of the retarder, should be protected against precipitation, moisture loss, contamination, and dispersal of the retarder by air movements. This protection should be applied immediately after the application of the retarder.

3.2.2.3.2. Where waterproof sheeting is used, it should be laid onto the surface of the concrete immediately after the retarder has been sprayed. It should be retained in position until immediately before exposing the aggregate.

3.2.2.3.3. Measures should be taken so that the protection system does not adversely affect the finish, line, or level of the concrete surface or the even distribution of the retarder. Where sheeting is used, measures should be taken to minimize air bubbling or blistering.

3.3. Exposing the Aggregate Surface

3.3.1. General

3.3.1.1. Brushing equipment should be used to expose the aggregates on the concrete surface. Where the brushing equipment is required to be supported by the slab, the concrete should have gained sufficient strength to avoid any damage to the concrete.

3.3.1.2. Removal of the protection system should take place as brushing proceeds. If waterproof sheeting is used as a protection system, it should be maintained in position until immediately before the brushing operation.

3.3.1.3. The contractor should complete the process of exposing the aggregate before the retarder becomes ineffective.

3.3.2. Brushing System

3.3.2.1. Sufficient brushing equipment capability should be maintained on the site in order to complete the exposure of the aggregate before the retarder becomes ineffective. Backup brushing equipment should be available on the site at all times for use in case of a breakdown or malfunction of the brushing equipment.

3.3.2.2. The brushing equipment used must be capable of producing an even macrotexture on the surface of the slab. Brushing should be carried out in the longitudinal direction of the pavement. The brushing equipment must be capable of maintaining an adequate brush rotational speed, which, in conjunction with the forward working speed, is sufficient to remove the surface mortar. Adequate dust suppression and collection measures should be in operation at all times.

3.3.2.3. The wheels of any brushing equipment that may run on the slab must be fitted with tires with a shallow tread pattern, low inflation pressure, and be sufficiently wide to avoid damage to the concrete.

3.3.3. Protection of the Surface Layer After Aggregate Exposure

3.3.3.1. Within one hour of completing the exposure of the aggregate, the surface should be dampened with water. A curing compound should be applied to the entire exposed aggregate surface of the slab.

3.3.3.2. In wet weather, the curing compound should be applied as soon as practicable after the rain stops. The surface may, alternatively, be cured using a wet mat curing process, provided it is maintained in a wet condition at all times during the curing period of the concrete.

3.4. Surface Macrotexture Depth and Remedial Measures

3.4.1. The texture depth of the surface of the concrete should be measured using the sand patch test (ASTM E 965). The average macrotexture depth of each 2500-ft. (762-m) section of highway lane, or each highway lane less than 2500 ft. (762 m), must be 0.7 mm, as defined by the FHWA’s Technical Advisory T 5040.36 - Surface Texture for Asphalt and Concrete.

3.4.2. During brushing, initial interim spot check measurements of the surface macrotexture depth should be made as soon as it is considered that the required texture depth has been reached. This should continue until the specified macrotexture depth has been achieved.

3.5. Defect Repairs

3.5.1. Defects may be repaired, provided the following conditions are met:

3.5.1.1. The affected area is removed down to the lower layer of the surface (higher quality) concrete.

3.5.1.2. A bonding agent is used, and the same mix design is used for the replacement concrete as was used for the original construction.

3.6. Renewal of Skid Resistance

3.6.1. After a period of years, it may be necessary to restore skid resistance to the exposed aggregate concrete pavement. Research is continuing into satisfactory in situ ways of carrying this out. Alternative methods of restoring the skid resistance include diamond grinding and overlay or inlay techniques using exposed aggregate concrete pavement or a thin surface treatment.

B.2 ROBUCO EXPOSED AGGREGATE SURFACE TREATMENT SPECIFICATIONS

The surface treatment shall be the exposure of the aggregate skeleton, as described hereafter.

1. Principle of the Technique

The procedure consists of evenly spraying a setting retarder onto the newly laid concrete surface.

The retarder shall be protected immediately after spraying by unrolling a waterproof sheeting onto it and weighting it down alongside the pavement. This sheeting shall be removed just before the surface mortar is brushed.

The “retarded” mortar shall be eliminated by wet or dry brushing with a steel wire brush no sooner than 24 hours after concreting. This minimum lapse of time shall be extended if the bulk of the concrete has not set sufficiently for the brushing machine to pass without causing any damage to the concrete.

2. Equipment and Products

2.1. Retarder

Dependent on the imposed depth of exposure, the use of a specific retarder is subject to the Administration's approval and the presentation of references.

The composition and viscosity of the retarder shall be such that it can be spread to an adequate rate all over the pavement, to ensure effective aggregate exposure.

The retarder shall contain a pigment in sufficient quantity to have an even clear color right after spraying.

Without being less than the minimum recommended by the manufacturer, the rate of spread shall be such that, after the surface mortar has been removed by the brushing machine, the results achieved meet the requirements in the sand patch test.

2.2. Sheeting

The retarder shall be protected by means of waterproof sheeting having a thickness of at least 50 micrometers.

A minimum 0.5 m extra width overlap shall be provided on both sides of the concrete slab.

2.3. Sheet Unrolling System

In order to minimize the effects of wind on the protective sheeting, the unrolling system shall release the latter as close as possible to the concrete surface.

Behind the unrolling system a burlap drag 4 to 5 m long shall be attached over the full width of the concrete pavement and towed over the unrolled sheeting, to press it well against the concrete surface.

In windy weather the burlap drag shall be sprinkled regularly with water, to keep it moist, so its pressing effect will be increased.

2.4. Brushing System

2.4.1. Brushes

Brushes shall be fitted with twisted steel wires having a diameter of 0.6 to 1 mm.

The length of the wires when new shall be at least 25 cm exclusive of attachment. Any brush shall be discarded as soon as its wires - exclusive of attachment - have become shorter than 10 cm.

2.4.2. Brushing Machine

The wheels of the brushing machine shall be fitted with wide tires having a low inflation pressure and a shallow tread.

The machine shall be equipped with one or two brushes meeting the requirements of section 2.4.1; in case of a single brush, it shall be mounted between the axles.

The machine shall be capable of maintaining a brush rotation speed that at the working speed is sufficient to remove the surface mortar in 2 or 3 passes.

It shall enable the height of the brush(es), as well as the bilateral extension to at least 30 cm outside the tire track, to be adjusted from the driver’s seat.

If the wet brushing method is used, each brush shall be equipped with a front spray bar for sprinkling water. An additional spray bar shall be mounted at the rear of the machine.

3. Procedure

3.1. Spraying the Retarder

The retarder shall be sprayed as soon as possible.

The spraying system shall spread the retarder evenly both lengthwise and across. This means that the machine must be capable of maintaining a constant working speed, or that the delivery of retarder must be a function of that speed.

Before work begins, the level of the spray bar, the delivery by the nozzles of the spray bar and the working speed of the brushing machine shall be adjusted so as to achieve the required rate of even spray of the retarder.

The area bounded by the spray bar and the system unrolling the protective sheeting shall be fully sheltered.

A manual spraying system shall always be available on the site for emergency use in case of a breakdown of the spraying installation.

3.2. Protecting the Retarder and the Concrete until Aggregate Exposure

Total protection of the retarder and the concrete shall be provided by waterproof sheeting to be unrolled evenly onto the concrete surface. This sheeting shall perform the same function on the concrete as a curing compound.

The laying of the sheeting must not affect the good finish of the concrete surface and the even distribution of the retarder in any way.

The unrolled sheeting shall be kept in place by ballast which shall be laid only on the extra width overlaps on both sides of the concrete surface to be protected.

Any air bubbling or blistering under the sheeting shall be avoided

3.3. Exposing the Aggregate by Brushing

Removing the sheeting and brushing with a steel wire brush shall be carried out 24 hours after concreting at the earliest, and as far as the bulk of the concrete has set sufficiently for the brushing machine to pass without causing any damage to the concrete.

The contractor shall take all appropriate measures to complete the aggregate exposure before the retarder used becomes ineffective.

3.4. Removing the Sheeting and Eliminating the “Retarded” Mortar

As the brushing machine is approaching, the waterproof sheeting shall be removed by sections of at most 75 m. The waste sheeting and mortar shall be carried off from the job site.

3.5. Protecting the Concrete after Brushing

One hour after brushing at the latest, a curing compound shall be sprayed mechanically and in a homogeneous way onto the entire concrete slab and its visible sides.

The rate of spread of the curing compound shall be at least 200 gr/m^2.

4. Results to be Achieved for Surface Texture

Texture depth by sand patch test, Hs, shall be statistically 1.3 mm ± 0.25 mm everywhere on the concrete surface, with a coefficient of variation, N, always smaller than 20.

To check compliance with surface texture requirements, at least 25 sand patch tests shall be performed at randomly selected spots; in any case a test shall be performed in every 50 m section constructed.

Check measurements shall be carried out as soon as possible after work has begun; if the surface as constructed is found to fall short of the requirements, work shall be stopped immediately and the surface shall be treated by scrabbling or grinding until the requirements are met. Work shall not be resumed without the consent of the Engineer, after the causes of the observed defects have been examined and eliminated.

Any new observation of inadequate surface texture shall give rise to the same measures of repair and examination, until the required results are achieved. The duration of work interruption, including the time required to adjust the construction procedure, shall not warrant an extension of completion time.

If the job on the whole does not conform to the specifications, the faulty areas shall be treated by scrabling or grinding until the entire surface meets the requirements.

The contractor shall provide in his tender any references available on the retarder which he intends to use in order to satisfy the requirements.

Apart from references to jobs already completed up to standard, the contractor shall be required to construct one or more test sections to the specifications. Each test section shall be at least 300 m^2 area and be constructed in concrete of the same composition and thickness as on the actual job to be carried out.

5. Implementation Survey

5.1. Development Overview

The patented exposed aggregate surface treatment for cement concrete pavements has reached its optimum stage of development.

This progress is demonstrated by the design, construction and further development of specific equipment capable of spraying, under optimum conditions, the retarder onto the concrete and at the same time unrolling polyethylene sheets out over the surface and keeping them in position on the fresh concrete. All problems can thus be controlled by strictly observing the rules for execution.

As for the technique, the fact that it has become so reliable can be ascribed mainly to the immediate protection of the retarder by the polyethylene sheet. Indeed, the latter enables the retarder to remain effective till the brushing operation, whatever the weather conditions.

Moreover, the polyethylene sheet presents a major advantage by offering a total protection of the concrete immediately after laying. As construction jobs are no longer stopped by rainfall, significant improvements are achieved in production and return rates and in the observance of completion times, while preserving a guarantee of good execution.

Efforts to promote the technique in foreign countries have yielded results, even though each country must first go through the conventional stage of trials on test sections before deciding to apply the procedure on a larger scale.

5.2. Site Overview

5.2.1. Austria

Thanks to the research of the Austrian Cement Industry, a two layer concrete pavement composition resulted in a revolutionary low rolling noise level, competitive with porous asphalt pavements. Several sites on the reconstruction of the A1 - “WEST-AUTOBAHN”, the A2 - “JDAUTOBAHN” and the A10 - “TAUERNAUTOBAHN” were performed. The Austrian road authority renews yearly approx. 500.000 to 700.000 m^2 of concrete highways in this way.

5.2.2. Belgium

After a development period of a few years, almost all (95%) cement concrete highways and motorways constructed from the beginning of the eighties through today are exposed aggregate.

5.2.3. France

Since 1985 there have been applications of aggregate exposure on cement concrete pavements especially by the construction or the overlay of highways (among them, partially the A6 “AUTOROUTE DU SOLEIL” and sections of the highways A10, A26, and A71).

Even a few national roads (RN) and departmental roads (RD) are aggregate exposed.

5.2.4. Great Britain

After a test section in 1991 on the AS-highway, the market for the exposed aggregate so called “whisper” surface treatment is very promising, and since 1993, real exposure sites on the MI 8 and others have been constructed.

5.2.5. Italy

Till now two successful aggregate exposure sites have been performed on rather small roads.

5.2.6. The Netherlands

In spite of the limited existence of cement concrete roads in the Netherlands, several sections of highways, a.o. the A1 and the A73, are aggregate exposed because of the very good noise properties of this kind of pavements. Due to this reason the city-bus reserved road pavements are also aggregate exposed concrete.

5.2.7. U.S.A.

With the well known interest of the U.S.A. for highways in cement concrete, also the star of the exposed aggregate surface technique is rising there. A first trial section with the so called “European Pavement” on the Interstate 75 Highway in the Detroit area has made his entrance.

5.2.8. Scandinavia

Finland: The ring road highway of Tampere 240.000 m^2
Sweden: The E6 Highway - Falkenberg 2 x 250.000 m^2
Highway E20 at Eskilstuna 260.000 m^2

Appendix C. Research Plan for Pervious Concrete Pavements

Objectives

The purpose of this work plan is to outline an approach to placing and evaluating hydraulic or cement-based pervious pavement.

The short-term goal is to design and build cement-based pervious pavements that focus on meeting highway demands. It is anticipated that a portland cement based surface course will be feasible for high-speed, heavy loaded roadways, with the purpose of lowering noise and improving splash/spray characteristics without compromising smoothness or safety.

The long-term goal is to design and build pervious concrete systems that provide improved functional properties for highway applications and low volume roadways along with stormwater management. Functional properties are non-structural properties including noise, smoothness, friction, splash, spray, cross-slope drainage, rolling resistance, reflectance, and permeability. The anticipation is that pervious concrete pavements will become a viable noise, splash, and spray reduction option for both low- and high-speed roadways, and will do so in cooperation with stormwater management efforts. All of this depends, of course, on long-term durability of the product.

Specific research objectives include finding optimal pervious concrete mix designs for wearing course sections in pavement applications. Information needed for the wearing course sections must address the issues of noise and skid resistance, assuming adequate strength and durability are developed. Constructability issues are also very critical. It is of paramount importance for the research to determine techniques that use existing concrete pavement construction equipment, including the conventional slip-form paver. At present the construction of pervious concrete sections is quite labor intensive. The use of pervious concrete as a wearing course entails construction of a concrete overlay in rehabilitation efforts. In new construction, two-course construction is a possibility. An evaluation of costs and time to construct will be included.

Understanding of Pervious Concrete

Definition and Potential Applications

For the purposes of this research plan, a pervious surface course is defined as a hard open surface (top) wearing course that is bonded to a structural pavement system that includes either a dense concrete or asphalt pavement. In this application, the system is designed such that water can pass through it, and out to the shoulder or ditch line. The primary purpose of the pervious surface is to reduce noise. Other functional benefits such as reduced splash and spray and improved skid resistance are also expected. Functional properties (non-structural) include noise, smoothness, friction, splash, spray, cross-slope drainage, rolling resistance, reflectance, permeability, and other similar properties.

A pervious surface course can be a key element of a stormwater management system when it is used over open-graded gravel, crushed stone, fabric, and/or a perforated pipe system—

collectively known as a stormwater management system. Pervious pavement also has potential as an urban heat abatement strategy.

Pervious concrete is a material with large voids intentionally built in. The resulting permeability allows for water (and air) to flow readily through this material. Concrete pavements are normally finished to be highly impermeable, just the opposite of pervious concrete. For use as a noise abatement system, pervious concrete is currently applied as a surface course and has provided not only low noise emission, but good drainage capacity (Sandberg and Ejsmont 2002; Beeldens, van Gemert, and Caestecker 2004; Nakahara et al. 2004).

Voids in pervious concrete are commonly created by using a uniform-graded concrete mix. In the United States, this type of mix is traditionally placed over a granular base that allows water to infiltrate directly into the groundwater system. Pervious concrete has been used almost exclusively in parking lots.

In a highway environment, two approaches should be studied. The first calls for a thin pervious surface course that takes all of the surface water down to an impermeable layer and out to the shoulder and ditch line. The second is an adaptation of the stormwater system in the shoulder that calls for the passing of water completely through the pavement section.

The critical difference with a high-speed application as opposed to more traditional “parking lot” applications rests with the toughness of the surface course. The durability of the material must be balanced with the porosity, adhesion, and clogging potential of each system. In the highway environment, a balance between water transport and noise reduction must be addressed, and it must be recognized as interdependent.

Materials and Mix Design

The uniform-graded aggregate distribution accounts for the porosity of the material. Cementitious materials and/or polymers in the system both form a film around the aggregates (for workability), and connect the aggregates together (for strength and durability). The demand for a rational mix design exists, as there are numerous competing properties including strength, porosity, freeze-thaw resistance, and workability (compactability).

Aggregates are uniformly graded between 1/2 inch and No. 4 sieve sizes and can consist of crushed material or rounded river gravel. A small amount of sand that passes the No. 8 sieve, but is retained on the No. 200, is beneficial for strength and workability. Mixtures typically have a sand-to-total aggregate ratio ranging from 5% to 10% (Wu and Nagi 1995).

Cementitious materials include Type I/II cement, fly ash, slag, and silica fume.

Admixtures may be used to improve constructability. Water reducers impact the water/cement ratio and retarders are often used as a means of delaying hydration of this very dry mix to assist in providing sufficient placement and curing time. Air entraining agents are also used to improve the freeze-thaw durability of the cementitious paste.

Pervious concrete pavements use a low water/cement ratio and thus extreme care must be taken to ensure that the appropriate amount of water is used in the mix and that the slab does not dry out prematurely. The aggregate moisture content and the amount of dust in the aggregate source must be determined as a part of the process to determine the amount of mix water.

In a stormwater system, typical pervious concrete mix designs used in the United States consist of cement, single-sized coarse aggregate (i.e., between 3/8 inch and No. 4 sieve size), and a water-to-cement ratio ranging from 0.27 to 0.43 (Schaefer et al. 2006). Reported properties of pervious concrete in the United States indicate that the 28-day compressive strength of pervious concrete ranges from 800 psi to 4000 psi, with void ratios ranges from 14% to 31%, and permeability ranging from 36 in./hour to 864 in./hour.

Construction

The subgrade or subbase material should be kept moist to prevent the mix water from being drawn from the slab. Transportation of the mix from the concrete plant to the jobsite is critical. Delivery of the concrete should be consistent and quick. Rear discharge trucks are better than front discharge because the steeper chutes assist in the discharge of the very stiff mix. Belt placers may be used in tight jobsites.

Current technology involves use of fixed forms. Work has been initiated by equipment companies to develop slip-form pavers that can assist in the placement of pervious concrete. Placement needs to be completed rapidly so that the slab does not dry out. The material is initially placed using a rear discharge concrete truck and then further placed by hand. Depending on the contractor's experience, three different methods have been used to compact the concrete:

- In the first method, a 1/2-inch to 3/4-inch spacer strip is placed on top of the forms and the concrete is leveled using a vibratory screed. Then, the spacer strip is removed and the surface is compacted using a hand pulled smooth steel roller. The steel roller is also used in transverse direction to finish the surface. The weight of the roller may vary but 100 lb per linear foot is common to produce the 10 psi of pressure suggested by Carolinas Ready Mixed Concrete Association (CRMCA).
- The second compaction method uses a vibratory plate compactor, which has only been used with mixes containing high angularity aggregate.
- The third method of compaction and finishing uses a roller screed; the stainless steel pipe rotates in an opposite direction to the direction of movement.

Care must be taken to not over-compact the slab. Following strike off, transverse joints are made with a joint roller called a "pizza cutter." Joints can be spaced from 20 to 45 feet apart. Immediately following the use of the joint roller, the slab must be covered with plastic sheeting that should remain in place for seven days. The sheeting must be anchored down to prevent wind from prematurely drying out the slab.

When pervious concrete is used as a surface layer, it may be placed using either a wet-on-wet or wet-on-dry process. In a wet-on-wet placement, better adhesion is provided between the layers; with wet-on-dry placement, the bonding between the layers can be improved by use of polymer-cement slurry (Beeldens, van Gemert, and Caestecker 2004). In both cases, the adhesion is subject to the quality of the construction. If care is not taken during construction, the bond will not develop, and the material can fail prematurely.

Due to differences in the properties of the pervious and dense concretes, stress concentrations at the interface can occur. The damage may take the form of an adhesion loss between the pervious concrete and the conventional pavement (Beeldens, van Gemert, and Caestecker 2004).

Acoustical Design

Regardless of the structural section, a pervious surface can help minimize tire-pavement noise, especially at high speeds. This is largely attributed to the reduction of key generation and amplification mechanisms, as well as acoustical absorption (Sandberg and Ejsmont 2002).

The recommended pervious concrete layer thickness can be calculated according to noise reducing requirements, and according to some preliminary work in Belgium and Germany, was found to be 40 mm (1.6 in.) for highway applications and 70 mm (2.75 in.) for urban settings.

Research from Purdue University's Institute of Safe, Quiet, and Durable Pavements has reported that sound absorption levels were improved when higher porosity of at least 25% was used (Sandberg and Ejsmont 2002; Olek, Weiss, and Neithalath 2004). It was also reported that a relationship exists between sound absorption and aggregate size: a decrease in aggregate size led to improved sound absorption (Olek, Weiss, and Neithalath 2004). Iowa State University did not include acoustic properties as part of their study; this will have to be validated in future work (Schaefer et al. 2006).

A combination of #4 and #8 aggregates in the mixture exhibited improved acoustic absorption characteristics when compared to straight gap grading. However, there may be some difficulty in controlling the gradation of these aggregates. A Belgium study reported sound reduction using pervious concrete as well, with a 5 dBA decrease using a pervious concrete pavement with only 19% porosity. This may be a more conservative but prudent number for high-volume, high-traffic loading facilities.

When compared to dense asphalt pavements (common in Europe), pervious concrete demonstrated noise reductions of 6 to 8 dBA for dry surfaces, and 4 to 8 dBA for wet surfaces. This study was conducted with cars traveling at speeds varying from 40 to 75 km/h (25 to 45 mph). For heavy trucks, noise reduction values were 4 to 8 dBA and 2 to 3 dBA for dry and wet surfaces, respectively. The lesser reduction is indicative of the greater contribution of exhaust and other noise sources in trucks.

Performance

Porosity and permeability versus strength and possibly durability may be a tradeoff with pervious pavements. For higher speed, high-traffic areas, lower porosity may simply be demanded to attain appropriate strength and durability characteristics in lieu of greater noise reduction.

Furthermore, mitigating freeze-thaw damage will be a challenge in the years to come. In pervious concrete, freezing tends to originate at the top of the pavement and infiltrate into the lower depths of the layer. Due to differences in the properties of the pervious concrete and underlying support, stress concentrations at the interface can occur. Damage may take the form of an adhesion loss between the pervious concrete and the underlying structural system.

When pervious concrete pavement was first constructed in Belgium, it was found to exhibit undesirable durability in freezing weather (Sulten 2004). Subsequently, polymer additives were used along with higher cement content. The result was a significant improvement in the service life compared to the first experiments.

When a pervious surface course is used, durability is commonly regulated by the interface of the two concrete layers. Once ice forms at the entrance of small pores and water is unable to move, damage in the form of raveling and localized cracking may soon occur if the mix has not been properly designed.

The U.S. Environmental Protection Agency reported that pervious concrete has been known to have a high rate of structural failure—about 75% (U.S. EPA 1999). “Poor design, inadequate construction techniques, soils with low permeability, heavy vehicular traffic, and resurfacing with nonpervious pavement materials,” have all shown to be attributing factors to the pavement’s failure (U.S. EPA 1999). Moreover, failures “often resulted in inadequate porosity” (McCormack and Son 2004). However, there have been pervious concrete pavements with void contents between 25 to 30% reported to be structurally sound (U.S. EPA 1999).

Clogging

One disadvantage of using pervious pavements is the clogging of the pavement’s pores. The pores will become less efficient over time due to deposits of dirt and dust in the voids from the road surroundings, from wear products from the pavement itself, and from tires (Sandberg and Ejsmont 2002; Olek et al. 2003). Continuous maintenance and cleaning is one method to help preserve and restore the pavement’s acoustical performance. It has also been reported by some that pore cleaning can occur during heavy rainfall and/or when vehicles travel at high speeds. It is theorized that water is pressurized at the “leading edge” of the tire-pavement interface, and dirty water is removed, by suction, at the “trailing edge.” The result is a “self-cleaning” effect.

Mechanized cleaning procedures are often used, including a combination of water blasting, dirty water suctioning, and vibrations transmitted by a plane of water between the water blasting and the suction.

The cost of cleaning can be high and needs to be addressed in its relationship to durability. One study from the Netherlands has shown that the cost of cleaning can be $4 to $19 per sq. yd. per year, depending on the process, time availability, collection and disposal system, etc.

Although clogging is an element to consider, the porosity of pervious concrete pavements is such that an extensive amount of clogging would have to take place to eliminate the hydraulic advantages. Most levels of clogging would have to exceed 90% of the voids before the pervious pavement would be impacted such that it would not function under a majority of rainfall events.

Double-layer pervious concrete is another demonstrated solution to the clogging issue. In this case, a top lift of pervious concrete with smaller aggregates is placed over a larger stone mix. The resulting system acts as a filter, which may help to minimize infiltration of debris causing clogging. The reduction in clogging will improve the acoustic durability of the material.

Construction Costs

The added cost of constructing pervious concrete pavement must be taken into consideration. The long-term effectiveness of this technique is also still under debate. In one report by the Belgian Road Research Centre, "extra costs as compared with a conventional concrete 22-cm (8.7-in.) thick as compared to a 4-cm (1.6-in.) pervious concrete laid over 18 cm (7 in.) of conventional concrete are estimated … as roughly 40%" (Descornet et al. 2000). However, "no significant cost difference with an equivalent structure including porous asphalt" was found (Descornet et al. 2000). The cost of constructing quiet pervious concrete pavements in New Zealand has been reported at US$132 per m² (US$111 per sq. yd.) (Clarke 2004). In the United States, pervious concrete projects have been reported to cost an additional 40% (Jacklet 2004).

Pervious Concrete Experience to Date

United States

Although there are many applications for pervious concrete, the vast majority of uses in the United States have been in car parking areas and very low volume roadways. Limited use along highway shoulders has also taken place. See Table C.1.

The success of pervious concrete has been mixed. The use has primarily occurred in warm weather states that don't experience hard, wet freezes.

Table C.1. Pervious concrete mix designs in the United States

	Tennis et al. 2004	NRMCA 2004	Schaefer et al. 2006
Cementitious materials	450 to 700	300 to 600	570 to 600
Aggregate	2000 to 2500	2400 to 2700	2700
Grading	3/4" to No. 4, 3/8" to No. 16, or No. 89		1/2" to No. 4
Water to cement ratio	0.27 to 0.34	0.27 to 0.43	0.27 to 0.35
Admixtures	Air entrainer	4%–8% air entrainer	10% latex, fibers
Binder to aggregate ratio		—	0.21

Note: Proportions give in lb/yd³.

Belgium

Belgium has had over a decade of experience with using pervious concrete surface courses. See Table C.2.

Demonstrated using the wet-on-wet procedure, a continuously reinforced concrete pavement is used as the base layer and cast with a conventional slip-form paver. After two to four hours, depending on the weather conditions, the top layer of pervious concrete is cast. This results in a good adhesion between both layers, since the pervious concrete and the concrete of the base course mingle into each other and a blended interlayer occurs. The advantage of this method is a good adhesion between both concrete layers. A disadvantage is the loss of porosity over the lowest part of the pervious concrete layer.

In the wet-on-dry method, the pervious concrete is placed on the hardened base course of concrete. To assure adhesion between both layers, an adhesive is used. Often, a polymer-cement slurry is employed for this purpose. The advantage of the wet-on-dry method compared with the wet-on-wet method is the independence of the interval time between the placing of the base course and the pervious concrete layer.

While used primarily for low-volume facilities including parking lots, quiet pavement applications using pervious concrete can be realized when used as an overlay. Noise reduction in such a composite system is a result of the pervious material’s acoustical absorption, while strength and durability are improved by the presence of the underlying structural layer. While in most cases, the structural layer will be concrete, it may be possible to construct a pervious surface course atop an existing asphalt pavement of adequate structural capacity.

When pervious concrete pavement was first constructed in Belgium, it was found to exhibit undesirable durability in freezing weather. Subsequently, polymer additives were used along with higher cement content. The result was a significant improvement in the service life compared to the first experiments.

Table C.2. Typical pervious concrete mix design in Belgium

	Type / Size	**Composition**	**Percent of Total Volume**
Cementitious materials	CEM III/A 42.5 LA	472 lb/cy	9.1%
Coarse aggregate	¼”to 7/16”	2275 lb/cy	49%
Fine aggregate	0 to 1/16”	150 lb/cy	3.3%
Water	—	94 lb/cy	5.6%
Admixtures	Polymer emulsion (50% solids)	94 lb/cy	5.4%

Reference: Beeldens 2004.

Germany

During the recent scanning tour to Europe, it was learned that the overall German experience with pervious concrete on high-speed roadways was very poor. The pervious concrete was reportedly placed with a modified asphalt finisher. While a reduction in noise was measured, the durability and skid-resistance of the pavement were repeatedly called into question. In the end, a decision was made to abandon this technology for high-speed roadways. See Table C.3.

Table C.3. Pervious concrete mix design in Germany

	Type / Size	Composition
Cementitious materials	CEM I 32,5 R	674 lb/cy
Aggregate	Moraine crushed stone, 5/16” to 3/8”	2,525 lb/cy
Admixtures	Fibers	1.5% (by volume)
Water to cement ratio	0.24 to 0.30	

References: Stegmaier 2003; Sulten 2004.

Japan

Current policy in Japan is to replace all pavements with pervious systems due to their safety and riding comfort. In order to change over their existing concrete pavements to a pervious system, one option is thin bonded pervious concrete overlays. Laboratory simulation tests have demonstrated that pervious concrete pavements can resist rutting and have a higher wear resistance to tire chains than porous asphalt. See Table C.4.

Pervious concrete pavements were evaluated in Japan with two experimental concrete sections, 200 mm (8 in.) in thickness (Descornet et al. 2000). The pervious concrete was placed with an asphalt paver. When compared to dense asphalt pavements, they displayed noise reductions of 6 to 8 dBA for dry surfaces and 4 to 8 dBA for wet surfaces; this study was conducted with cars traveling at speeds varying from 40 to 75 km/h (25 to 45 mph). For heavy trucks, noise reduction values were 4 to 8 dBA and 2 to 3 dBA, respectively.

Table C.4. Typical pervious concrete mix design in Japan

Aggregate Gradation	Mortar / Gravel	Unit content (lbs/cy)				
		Water	**Cement**	**ARM Admixture**	**Fine Sand**	**5–13 mm & 1.2–5 mm Gravel**
5/16”	57%	155	530	177	352	2400
1/2”	50%	138	492	165	334	2532

References: Kajio 2004; Nakahara et al. 2004.

Research Scope

Not one single element of pervious concrete can be considered as satisfactorily known and understood. A great deal more work needs to be done on the development of mixes that can handle the anticipated multiple functions of pervious pavements. This product must be tough enough to handle high loads, drain water to the shoulder, and reduce noise, without compromising smoothness, friction and long-term durability. Laboratory study is necessary to determine the right balance for all these properties.

The following elements should be considered in the potential scope of the research plan:

- Extension of current laboratory studies will be undertaken to investigate the behavior (strength, porosity, permeability, clogging, freeze-thaw) of pervious concrete made with various aggregate types and mix proportions used across the United States. These efforts will include determining the basic requirements for aggregate quality, aggregate gradation, concrete and admixture proportions to produce the proper strength, porosity, permeability and freeze-thaw resistance of pervious concrete. As recent work has shown the importance of compaction energy on pervious concrete results, laboratory studies and evaluation of placement and compaction techniques for pervious concrete will be undertaken to evaluate the density, porosity, and strength of selected mixes of pervious concrete as a function of compaction effort. Comparison placement techniques of vibratory screed and rolling compaction in laboratory scale model tests will be used to evaluate paving methods to optimize the use of existing paving equipment.
- Following more extensive mix design studies, evaluation of design thickness requirements for wearing course pervious concrete pavement sections will be undertaken. Initially this will entail laboratory determination and evaluation of noise and skid resistance properties, and laboratory evaluation of thickness and constructability. This will be followed by field trial sections for the evaluation of in-place pervious concrete properties and for determination of surface characteristics of pervious concrete pavements, including noise and skid resistance properties.
- Wearing course applications must involve the development of sufficient bond between the structural layer and the wearing course. Evaluation of the required bond strength and how to develop it will be completed. The evaluation will include wet-on-wet construction as well as wet-on-dry. Durability of the wearing course will be paramount to the success of pervious concrete applications. Use of high strength cements and admixtures will be evaluated for effectiveness in addressing durability.
- For wearing course applications the effect of clogging and maintenance efforts on the material properties of placed concrete will be evaluated. Both laboratory and field scale tests are proposed, with evaluation of splash and spray and freeze-thaw resistance of pervious concrete pavement systems evaluated, again, at both laboratory and field scales.
- Field trial sections will be placed for evaluation of in-place pervious concrete properties and performance. At the present time, field installations are being considered at the MnROAD low- and high-volume test facilities to enable well-instrumented sections to be carefully monitored and also allow noise and splash studies to be conducted. The noise studies will be coordinated with the current Concrete Pavement Surface Characteristics Project underway at the National Concrete Pavement Technology Center. Field constructability issues will be addressed to develop methods of placement using existing equipment or equipment with appropriate modifications for placement of pervious concrete. Field trials could involve single-lift and two-lift construction. The single-lift would utilize standard overlay practices and the two-lift could examine wet-on-wet construction of the thicker overlays. The field trials will also investigate different curing methods to address the concern of applying plastic sheeting on large volume projects.

In addition, the knowledge learned about porous asphalt should be examined in detail, especially the clogging effects on noise and drainage as a means of assisting the extension of baseline information.

Research Tasks

The research plan has been organized into five tasks:

1. Mix Design and Analysis
2. Pervious Surface Course Integrated with Stormwater Management
3. Wet-on-Dry Placement of Pervious Surface Course over Concrete and HMA
4. Wet-on-Wet Construction of Concrete Pavement with Pervious Surface Course
5. Performance, Maintenance, Repair, and Replacement of Pervious Concrete

Note that the tasks don't necessarily need to be accomplished sequentially.

Task 1. Mix Design and Analysis

As pervious concrete progresses from full-depth parking lot type applications to surface wearing course use in the United States, certain obstacles must be overcome to produce a durable surface. Pervious concrete used as a surface course will be subjected to much more extreme conditions and the mix design must be optimized for strength, permeability, and especially better freeze-thaw durability.

The primary concern for surface course pervious concrete is noise reduction and skid resistance. For surface course applications, aggregate size and gradation will need to be adjusted to achieve higher flexural strength, above 500 psi, most likely decreasing permeability. A method for increasing tensile strength and permeability is the use of fibers in the mix. A recent study used only one fiber type and a study needs to be performed to determine the effect of fiber type on the mix, in order to optimize the mix design (Schaefer et al. 2006). The high level of exposed surface may make pervious concrete especially susceptible to deicer scaling and could cause premature failure. There is currently no data in the literature about the effect of deicers on pervious concrete. There is also a debate currently on the use of air entraining agents in pervious concrete. The amount of entrained air and the effect of air entrainment on pervious concrete properties and durability need to be investigated. Once the chemical durability of mixes has been established, the mechanical durability and abrasion resistance of pervious concrete for use as a surface course needs to be investigated. To maintain skid resistance and achieve the goals of a permeable pavement, the pavement must maintain its permeability under service conditions. Thus a clogging test will need to be developed to aid in designing pervious concrete maintenance schedules for optimum performance.

The mix design will be optimized for aggregate surface area, paste thickness and fiber addition rate. Aggregate surface area will include three different sizes of aggregates, each with three sand dilution rates (nine variables). Initially, three paste mixes will be used to determine the paste-to-strength relationship (three variables). Three fiber addition rates will determine if fibers are needed in the lower void ratio mixes and at what addition rate (three variables). Depending upon the variability of the coarse aggregate surface area, four or five surface area combinations will be selected to yield a total of about 50 mixes. The criteria for the MOR will be greater than 500 psi. A target minimum permeability of 12 inches per hours will be used.

The best performing mixes will be subjected to potassium chloride, calcium chloride, sodium chloride, sodium acetate, and calcium magnesium acetate deicers according to ASTM C 672.

Throughout the test, mass loss and compressive strength will be tested to aid in determining deterioration.

Samples with and without air entraining agent will be subjected to rapid and slow freeze-thaw testing, with and without deicers. Air void structure will be analyzed using the scanning electron microscope to determine if any air entrainment occurs and if the air entrainment provided any paste protection.

Selected mixes will be tested for abrasion resistance. The detailed test methods have not yet been determined. A key aspect of field performance will be how well the surface of pervious concrete wearing courses performs when subject to snow blades and thus a test to mimic such action is necessary.

The mixes selected for abrasion resistance will also be subject to clogging tests. At present no tests have been developed to determine the clogging characteristics of pervious concrete mixes and thus test development will be necessary. Currently permeability is determined on the basis of test methods used for soils. An evaluation and development of appropriate laboratory and field permeability tests particular to pervious concrete is necessary to properly assess the movement of water through the pervious concrete.

Following study of the mix design issues, procedures for overlay design will be developed. This effort should be conducted in parallel with current National Concrete Pavement Technology Center efforts to streamline concrete overlay designs. A key issue to be understood in the overlay design is the bond strength that can develop between pervious concrete overlays and both existing and new concrete and hot-mixed asphalt pavements. Laboratory studies will be undertaken to test bond strength between pervious concrete and the base pavement to determine required overlay thicknesses.

The workability of pervious concrete cannot be measured using a standard slump one. Pervious concrete that is too dry does not flow out of the truck and increases the difficulty in placement, which affects costs and efficiency. A new test method is needed to allow workability of pervious concrete to be determined in the field, allowing a contractor to test for desired workability and assist in making field additions of water to produce the desired characteristics. For pervious concrete to be used in surface course overlays, field curing without the use of plastic sheets, as is current practice in parking lot applications, must be developed. Different curing methods will be evaluated to determine their effectiveness in prevention of drying and the maintenance of a positive curing environment.

In conjunction with the present Concrete Pavement Surface Characteristics Project at the National Concrete Pavement Technology Center, noise and splash/spray studies will be conducted after selected mix designs are placed in the field.

The paste (cement, sand, water, additives and admixtures) must be the focal point of the next round of laboratory testing. The paste must have multiple properties and a balance between adhesion properties, elasticity, and brittleness. An examination of a wider range of polymers is critical and researchers should look at work done under high performance concrete for bridge systems.

The research team should work with other researchers, for example at Purdue University, to determine what test protocols can be used to examine the acoustical properties of pervious concrete. Their initial work done on pervious concrete does examine certain test procedures.

Iowa State University has taken an important first cut at developing a mix design approach to pervious pavements. The next step is to validate the procedure. This would ensure that the details imbedded in the procedure are properly stated and repeatable. It would also assure that others have the opportunity to suggest modification, improvements, or innovations to the process.

While this step addresses the laboratory mix design, the plant that produces the final mix should follow identical procedures using actual materials that will be incorporated into the work. This is referred to as the mix verification process.

The work should also address additional aggregates with higher engineering properties than used in the original Iowa State University study. To create freeze-thaw durable pervious concrete mixes that will function throughout the United States, the work will have to be validated with a larger variety of aggregate, which represents typical varieties found across the country. This work should lead to establishing minimum aggregate quality to produce durable pervious concrete. It may be necessary to list rheological and mechanical properties to be tested for acceptance.

More work is needed to determine the relationship between compaction energy and pervious concrete properties including strength, void ratio, permeability, and freeze-thaw durability. In addition, the following elements must be addressed:

- Evaluate various compaction requirements in the lab and ways to connect this to a field test.
- Evaluation of the acoustical properties should include both laboratory tests (e.g., impedance tube testing) and field tests that gauge the effect at (close to) grazing incidence such as the effective flow resistivity test.
- Evaluate more than one polymer type.
- Evaluate different fiber types, possibly steel and polypropylene mixes.
- Evaluate critical tolerances in the gradation, and consider how gradation changes influence porosity and compaction.
- The question of air entrainment is important. The porosity of pervious concrete is achieved by a deliberate uniform graded aggregate and paste matrix designed in such proportion and placed with such a manner as to provide interconnected voids. Air entrainment will be in the paste.

Task 2. Pervious Surface Course Integrated with Stormwater Management

The purpose of Task 2 is to place the robust mixes designed in Task 1 on parking lots or very low, lightly trafficked roadways to evaluate the mix and get an initial sense of the mix’s performance capabilities.

It is suggested that a partnership be developed with the places the mix that eventually could be used independently as a surface course but test it in a stormwater management environment.

There are many more opportunities to build these types of sections. Admittedly this is cautious. However, there are very few acceptable pervious pavements in the world right now and the method deserves caution, both regarding the initial expense and also from a safety standpoint.

The following subtasks should be considered in this work:

- Design, place and evaluate new mixes over granular bases by building test strips, focusing on parking lots and very low volume roads, using forms and heavy roller compactors or modified asphalt pavers.
- Evaluate new mixes with clients interested in stormwater management systems.
- Develop typical sections for thin overlays to address surface drainage, shoulder matching, and curb and gutter details.
- Address equipment issues such as mix plant, transport, placement, finishing, and curing.
- Address mix property variability, final product acceptance criteria, and other quality control issues.
- Evaluate the toughness of the mix for raveling or close-up, clogging, ice formation, and the functional characteristics of the pavement: noise, skid, smoothness, etc.
- Develop an acoustic monitoring plan specifically for this product. Look closely at the acoustic properties and the clogging versus the water permeability. A relationship between acoustics and water needs to be established.
- Evaluate various geometrics and typical section details, calculating cross-drainage quantities along with transport speed, elevation matching, and infiltration into ground water or ditch line.

Expected results:

- Validation of the various mixes, including quality control methods to monitor the mix
- Better assessment of placement and compaction requirements

The mixes that are designed for use in stormwater management could be used in test strips as a precursor to Task 3. Placement over granular materials eliminates the potential complications of selecting proper substrates as proposed in Tasks 3 and 4.

Task 3. Wet-on-Dry Placement of Pervious Surface Course over Concrete and HMA

This task involves evaluating the construction of a pervious surface course over existing pavement structures. The task involves addressing the structural adequacy of the substrate, the cleaning and bonding needs, and the joint and crack filling requirements. The following subtasks should be considered in this work:

- Place mixes from Task 1 on higher volume and higher speed roadways on both concrete and asphalt substrates.
- Assess bonding requirements, joint details, and smoothness needs.
- Evaluate the ride quality, noise, friction, and splash/spray, as well as clogging and cleaning.
- Develop a draft construction specification.

For pervious over existing concrete pavement, it is suggested that continuously reinforced concrete pavement (CRCP) or crack free thin jointed concrete pavement be used. This will minimize joint repairs and will allow a cleaner evaluation of bonding methods. It will also collect the most water and transport it to the shoulder. Shoulder and run off details must be addressed.

For pervious concrete over existing asphalt pavement, the underlying pavement should be relatively clean hot mix, again crack free and rut free. One issue that will have to be faced is the stripping potential of the asphalt layer. The bonding agent may also have to act as a sealer to allow flow to the shoulder and not to pond at the interface.

Expected results:

- Effectiveness of mixes on higher volume roads
- Assessment of need for and effectiveness of bonding requirements for different substrates
- Assessment of need for and effectiveness of various jointing details
- Draft construction specifications

Task 4. Wet-on-Wet Construction of Concrete Pavement with a Pervious Surface Course

This task includes placing a two-course concrete pavement with pervious concrete surface course using the full array of conventional concrete pavement equipment. The focus of the task will be on construction techniques, using central mix, agitator trucks, and slip-form paving techniques exclusively.

This is probably the most difficult element of the research plan in that several factors will be combined in this operation. All characteristics, including the ride quality, noise, friction, and splash/spray as well as clogging and cleaning will be evaluated.

As part of this task, it will be necessary to develop typical section details that address the following:

- Truck lane selection versus entire pavement
- Shoulder details, including elevation
- Multiple lane cross-drain factors
- Two-lift construction techniques
- Wet-on-new dry construction to evaluate bond strength
- For thin sections to be both quiet and drainable, how much is infiltrated into the bottom layer in a wet-on-wet construction process?

Expected results:

- Initial assessment of whether conventional concrete pavement equipment will work without major changes
- Effectiveness of mixes on higher volume roads

Task 5. Performance, Maintenance, Repair, and Replacement of Pervious Concrete

This task is the development and implementation of a performance evaluation program. The first step in this Task is to examine the project over time while in service. The evaluation should include a full range of pavement tests—smoothness, friction, distress surveys, clogging, and acoustical properties.

The clogging issue must be examined for both permeability and acoustics. The clogging may impact one but not the other, as there is some evidence that clogging from sandy material may not impact acoustics as it will the permeability. Noise changes based on clogging will be determined. European experiences note that it is a factor. A de-clogging program using vacuums and water dispersion methods will be developed and implemented.

Repairs necessary because of substrate failures need to be examined as well. A review of the older sections in Europe might provide clues into how this can be best done.

This task will include an evaluation of removal and replacement technologies, including recycling. The life expectancy of pervious surfacing must push 10 years or more without significant changes in noise or permeability to be anywhere near cost effective. Removal and replacement work and possibly a recycling technique should be explored. Fibers and polymers both may have a negative impact on this operation. Milling and recycling a concrete pervious surface with latex and/or fibers would be more difficult than an asphalt-based product.

Expected results:

- Performance reports
- De-clogging program
- Repair timing and repair techniques
- Rehabilitation timing and replacement techniques

Research Schedule

The initial research plan should be accomplished over a five-year period. This would include the initial demonstration sites on low speed facilities and also the high-speed highway applications. The ongoing evaluation of the noise, friction, and durability levels will extend beyond the initial five-year period until the measured levels stabilize.

Coordination and Collaboration

Multiple partners are envisioned, including Federal Highway Administration, U.S. Environmental Protection Agency, American Concrete Pavement Association, National Ready Mix Association, and state departments of transportation. Preliminary discussions have been held with Minnesota DOT personnel regarding potential placement of a pervious concrete section at the MnROAD test facility.

Initial Steps

It is suggested that the following steps be completed to initiate the research:

1. Establish a team to improve and validate the research plan.
2. Establish a budget.
3. Establish partnerships with other organizations.
4. Convene the Technical Advisory Panel.
5. Update the research plan, based on comments received.
6. Establish help desk and national outreach.
7. Organize laboratory experiment phase.
8. Organize pilot projects and evaluation phase.
9. Organize major roadway trial phase.
10. Prepare all critical documents and deliverables.

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