Developing Quieter Concrete Pavements

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Abstract

The American Concrete Pavement Association (ACPA) is conducting research to develop quieter concrete pavements to better serve the transportation community. This effort involves standardization of tire/pavement noise assessment; establishment of acoustic performance curves for existing surfaces; development of new surface textures through a laboratory test program; a field validation program; and an implementation phase.

The acoustic performance of pavement surfaces needs to consider the characteristics throughout the pavements service life and not just the as-constructed condition, or the nearly new pavement conditions. Longitudinally tined , astro-turf drag textures, and diamond grinding provide the quietest new construction techniques, while diamond grinding provides the quietest rehabilitation strategy. Most loud concrete pavements have been constructed using transverse tining.

The development of new surface textures requires the ability to easily modify surface characteristics and to readily evaluate their impact on acoustic performance. To accomplish this, the ACPA has contracted with Purdue University to conduct laboratory testing using the Purdue Tire Pavement Test Apparatus (TPTA). The TPTA provides efficient evaluation of any surface that can be cast or formed. Efforts to date have focused on development of quieter diamond ground surfaces through alteration of the blade size, spacer arrangements, and by controlling fin profile.

The research presented in this paper is concerned primarily with exterior vehicle noise. Although both interior and exterior noise is important to the consumer, most agency regulations involve only exterior noise and as such this is the focus of the current research.

Introduction

Pavement texture is a critical aspect of tire/pavement noise, frictional properties and ride qualities. Figure 1 indicates the effect shown by colors, of the different texture classifications (eg micro, macro, mega & roughness) and the related pavement factors such as noise, friction, rolling resistance, etc. It should be noted that the texture classification are based on wavelengths as indicated in Figure 1. It should be noted that modification of surface texture to improve one of the pavement factors could have an adverse affect on other pavement factors. Therefore, any optimization of pavement texture should consider all the factors accordingly.

Historical Texture Development in the US

Roadways have been constructed out of concrete pavements in the United States since the late 1800s. Numerous surface textures have been produced including burlap drag, astro-turf, uniformly and random transverse tined, longitudinally tined, and both profile and whisper diamond grinding processes. Each surface evolved for specific reasons.

In the early days, concrete pavements were constructed with fixed forms and hand placement techniques. Transportation speeds were relatively slow and most pavements were primarily intended to get the country out of the dirt. Surface texture properties were often the result of the concrete finishing or curing technique.

The first slip form pavement construction occurred in the late 1950's. This form of construction significantly improved PCCP production and marked the beginning of the end for hand placement methods. At this same time, automobile speeds were increasing and improved textures were desired to provide increased frictional properties. During most of the 1950's and 60's, this challenge was met by using various forms of drag or broom textures. Drag textures were typically produced by using burlap or belt material and literally dragging it behind the paver. Broom textures were imparted by applying a natural bristle broom to the final surface to create striations in the finish. By 1963, sixty percent of the state highway departments allowed the use of burlap drag to produce the final surface texture.

As time progressed, traffic volumes increased causing greater surface wear resulting in reduced frictional properties. This created increased interest in deeper surface textures. Natural bristle brooms were being replaced with wire brooms and heavier drags were being experimented with including multiple layers of burlap.

The first major innovation in surface texture techniques was introduced in 1965 with the use of diamond blades to saw longitudinal grooves into the pavement surface. This was first accomplished in Los Angeles to solve wet weather accidents occurring on curves[1]. Accident reductions as high as 90 percent were reported at the time[1]. This technique was so successful that the California Division of Highways constructed almost 95,000 yards of this treatment in 1967.[1]

A number of patterns were evaluated by California including V grooves, rounded grooves and different spacing arrangements. This work was performed to evaluate the increase in friction factor, wear resistance, and possible vehicle handling problems. Most of this work was accomplished in the longitudinal direction. By 1969, it had been determined that rectangular shaped grooves, 1/8 inch in depth by 1/8 inch in width spaced ¾ inches apart were advantageous. Grooves ¼ by ¼ inch were found to produce undesirable vehicle control issues for motor cycles and light vehicles. Subsequent accident investigations had found no difference in performance between the ½ inch cc and ¾ inch cc spacing and therefore the latter spacing was selected. Subsequent work indicated that 0.095 inch grooves widths provided still further benefits for motorcycle control. During this early work California was cognizant of the impact of the various surface techniques on tire noise, tire wear, texture durability, and wet weather issues such as splash and spray. The following quote by Francis Hveem in 1955 indicates noise is not a new issue to highway agencies [2]: "The question of noise, or the effect of noise upon people is becoming a matter of concern to many agencies and individuals. With the spread of industrialization and the more rapid tempo of modern life, there is increasing resentment toward unnecessary noise and a consciousness of need for peace and quiet."

The decade of the 60's began and ended with the principle texture method consisting of the use of burlap drag textures. By the end of the decade, 46 states allowed the use of burlap drag textures. However, increasing traffic speeds, volumes, and loads, were increasing texture wear and decreasing pavement friction. This was resulting in increased research on pavement friction and roadway safety.

The 1970s can be considered a renaissance for friction and highway safety research. While almost all states allowed the use of burlap drag or some combination of drag and broom textures at the beginning of the decade, at least 33 states required or were planning to require tined textures by the end of the decade. At least 11 states conducted field evaluations of various tining and texturing methods to define the optimum texture. Some of the more comprehensive experiments were conducted by California, Texas, Georgia, and Virginia.

In the early to mid 1970's, most states adopting tining had selected uniformly spaced transverse tining spaced at ½ inch or ¾ inch with the former being most common. Groove dimensions were typically 1/8 inch wide by 1/8 to 3/16 inch deep. Although at least one agency recommended the use of random tining (1/2-3/4) this was never implemented by any state.[3] Virginia was the first state to adopt longitudinal tining (1974) followed closely by California (1977). [4,5] These were the only two states to adopt longitudinal tining during the 1970s.

One of the more interesting experiments conducted during this time was the Virginia study which evaluated a range of texture types including both longitudinal and transverse tining, exposed aggregate, dimpled or imprinted texture, combination of longitudinal and transverse, sprinkled aggregate (e.g. aggregate broadcast onto the surface), and drag textures.[4] This study evaluated friction, noise, and roughness, as well as constructability issues. The noise results indicated that the exposed aggregate, sprinkled aggregate and dimpled texture all produced greater noise than the tined sections. The 1 ½ inch transverse tined section also produced some undesirable noise within the vehicle and this section was not recommended for further evaluation.

Between 1974 and 1976 four major organizations authored texturing recommendations. Specifically, the Federal Highway Administration (FHWA), Portland Cement Association (PCA), American Association of State Highway Transportation Officials (AASHTO) and the ACPA. All except the ACPA recommended transverse tining as the preferred method. The ACPA provided spacing recommendations without preference to orientation, as well as, allowing the use of random spacing (1/4 to 1 inch). In 1979, the FHWA prepared a new Technical Advisory that again recommended transverse tining and required other methods to be based on sufficient performance analysis to justify their use. California was the only state to prepare technical justification to use longitudinal tining. The only change that California made to their 1969 original recommendations for longitudinal grooving was to increase the depth from 1/8 inch to 3/16 inch to better accommodate texture wear.

The 1980's saw only limited research on new texturing techniques with the most notable being the introduction of the astro-turf drag method. What research was conducted focused mainly on increasing tine spacing and heavier drag textures and the combination of the two. Research from the previous decade suggested that combining drag textures with tined textures provided better friction properties and sometimes lower overall noise. Minnesota included the combined treatments in their texture research at this time and confirmed the benefit of the combination.[6]

The decade of the 1990s was marked by the largest research efforts to date directed primarily to the noise issue. The Wisconsin/Marquette studies represented the first major breakthrough in the re-introduction and eventual use of random transverse tining. Wisconsin became the first state to adopt random transverse tining as their standard practice. Other states followed. The movement towards random tining was an acknowledgment by the highway community that uniformly spaced transverse tining had produced textures with very tonal properties. As noise became an ever increasing issue, ways to enhance the texture characteristics were sought. Unfortunately, one of the negatives of the implementation of the random transverse tining was the introduction of larger tine spacing. Although most earlier work had suggested this was not desirable, the random patterns were implemented with spacing as large as 3 inches. None of the recommendations from the 1970's to implement narrow spaced random textures were implemented. Only the wide spacing was implemented. The result of this was that the overall noise levels were often raised in locations where it was tried. In addition to the use of random transverse tining, the Minnesota DOT (MNDOT) implemented the use of astro-turf drag texture as their standard practice in 1999. This texture is still used today by MNDOT and produces one of the quietest textures currently available for use. MNDOT requires a minimum of 1 mm of texture depth to ensure adequate frictional properties and improved their mix designs to ensure durable surface textures.

Since the turn of the century there has been a renewed interest in pavement texture and reducing noise levels. Communities are taking an active interest in ensuring quieter highways in the urban centers with high traffic volumes. The US transportation industry has sponsored more noise related research since 2000 then in the history of transportation. Many states have or are considering implementing longitudinal texturing to reduce noise. Still others are experimenting with the astro-turf texture implemented by Minnesota.

Measuring and Designing for Noise in the US

Noise Design Methodology

In December of 2004, the FHWA began requiring the use of a new traffic noise modeling procedure called TNM 2.5 (**T**raffic **N**oise **M**odel). The use of this new software is required for agencies to conduct noise mitigation analysis on Federally funded projects. The new methodology replaced the older software, called STAMINA, which was developed in the early 1970s in a four state study. Since the development of STAMINA, many changes have occurred including fleet changes on the highways, and significant improvements in both software and noise modeling enabling a more sophisticated approach to be taken. The new study, began by developing a national **R**eference **E**nergy **M**ean **E**mission **L**evel (REMEL) database.

To develop the new database/software, the FHWA initiated a national pooled fund study, comprised of twenty five states, to conduct new measurements. The measurements, obtained between July 1993 and November 1995, were obtained at 40 locations across the country. Measurements for both PCCP and AC surfaces were obtained from eight states. PCCP measurements were obtained in California, Michigan, Tennessee, and Maryland. At each measurement location, a microphone was placed 50 ft from the center of the nearest travel lane at a height of 5 ft. Statistical pass-by measurements were then obtained. Approximately 6,000 individual pass-by measurements were obtained for the study.

Statistical pass-by measurements evaluate the maximum noise generated by each individual vehicle as it passes by the measurement point. This measurement includes all noise produced by the passing vehicle; drive train, tire/pavement, exhaust, etc. For this study, traffic was assigned to five different categories: motorcycle, bus, auto, medium truck, and heavy truck. When considering the effect of surface type, the latter three categories dominate the results.

Table 1 indicates the locations, pavement age, and assumed texture type for each of the PCCP test locations [7]. Since the final report does not stipulate PCCP texture type, it has been assumed, based on location and pavement age. Table 1 also indicates the roadway grade for each of the pavement locations. It should be noted that the effect of grade was only evaluated on California pavements using longitudinal tining.

TNM Results

The new TNM software has many advantages over the previous software. For one, it can evaluate the effect of four different pavement types; Average, Dense Graded AC; Open Graded AC, and PCCP. The average pavement is arrived at by combining approximately 75% dense graded pavement results with 25% PCCP pavement results. Currently, the average pavement condition is the only approved surface type that can be used in modeling. The only exception to this is the Arizona Quiet Pavement program where surface type affect has been allowed.

During the original TNM development work (Version 1.0), the results shown in Table 2 were generated. These results indicate the effect of each of the three other surfaces when compared to the "average pavement" required for analyses. For example, if the analysis was conducted using a dense graded surface instead of the average pavement, the resulting noise level for an automobile would be reduced 0.65 dB. Similarly, if a PCCP surface were substituted for the average pavement, the noise level would increase by 2.36 dB. For heavy trucks, there is less of an effect from surface type. However, there is still an effect.

At first, the use of the average pavement condition may seem to be an advantage for PCCP pavements. However, there are two concerns to this approach. The first concern is illustrated in Figure 2. As indicated in the cumulative distribution plot, three of the data points were eight years or less in age and the remaining points were between 25 to 43 years in age. Since it is likely that the older pavements would have experienced faulting, the statistical pass-by method would have considered this part of the total pass-by event noise. As such it does not represent a surface type as much as it does a pavement condition. If the pavements had been significantly faulted, they could be assigning a higher than necessary value to PCCP.

On the other hand, had the pavements been in very smooth condition, and constructed with a burlap texture that had long ago worn off, they could be quieter than typically found on transverse tined pavements and this represents the second concern. In this condition, the modeling would indicate a quieter pavement than was built. This would mean the noise abatement measures could be inadequate resulting in consumer dissatisfaction when the project is opened to traffic. Both situations are unfortunate for the concrete pavement industry. In either event, a good case could be made that pavements constructed in the 1950's and 60's do not represent the concrete pavements of today.

Since the development of the Table 2 in 1995, TNM has undergone several revisions to become version 2.5. It is not known at this time whether these same differences exist. However, no new data has been collected for the development.

The development of the FHWA TNM software marked a major milestone in refinement of noise mitigation tools. The new TNM provides expanded capability and enhanced analysis. However, the data upon which the concrete pavement analysis is conducted may not represent pavement textures commonly used today. Since the late 1970's, many states have used uniformly transverse tined pavements. These textures do not appear to be properly represented in the TNM database. Additionally, the more recently developed textures such as random transverse, astro-turf, etc are not represented at all. Furthermore, for the textures that were represented, the age of the pavements appears to be too old to adequately represent concrete pavements. Pavements still within their original design life should be evaluated and used in the database.

To select the appropriate pavement sections for any future improvements in TNM, it will be necessary to address the acoustic performance period for the design life. That is, what is the best way to represent the pavement for its design life. Is it the performance at 10 years for a twenty year design life or some other metric.

The FHWA/Volpe Center is currently looking at a feasibility study to determine if source measurement techniques such On-Board Sound Intensity (OBSI) can be used to modify the

REMELS to develop texture specific models. The following section will discuss the OBSI techniques and there importance to tire/pavement noise measurement.

Testing for Noise

Field data for the REMEL models described previously are obtained by measuring total traffic noise at a distance of 50 ft from the center of the outside lane at a microphone height of 5 ft. This type of testing is called wayside testing and is the type of noise measurement endorsed by the FHWA. However, this type of measurement is relatively time consuming to conduct and generally expensive. They are also limited in that they cannot directly measure just the noise generated by the tire/pavement interface and are influenced by traffic operations and environmental conditions.

Since the pavement surface characteristics are one of the few variables an agency has control over, the tire/pavement noise is an important consideration; especially since it typically dominates at highway speeds. To accomplish this, techniques known as near field or close proximity (eg CPX) have evolved. This form of measurement places microphones within inches of a test tire and only a couple of inches above the roadway surface. There are two forms of this testing currently conducted. In Europe, there is a draft ISO CPX standard using sound pressure levels (SPL). This draft standard has been in existence for over ten years and is the predominate form of near-field measurement. In the US, the OBSI method is the most common measurement procedure with approximately ten systems in current use or soon to be. Only two ISO CPX trailers are currently in operation in the US.

The CPX method generally requires the use of a towed trailer to isolate the microphones from wind noise and external noises. The OBSI system attaches to the lug nuts of a common passenger car and eliminates the need and expense of a trailer.

On-Board Sound Intensity Methods (OBSI)

During the early 1980s, General Motors, Inc. developed a research method for evaluating noise generated by the tire/pavement interaction [8]. These procedures were essentially unknown to the US highway agencies until 2002 when Caltrans began researching and promoting its use. The first implementation of the OBSI by Caltrans used the GM design as shown in Figure 3. This system was extensively evaluated by Caltran's to rank different pavement types and to develop comparisons to both wayside measurements and the two CPX trailers in use in the US [9]. Caltran's research indicates that the OBSI test results are typically 3.4 dBA higher than the CPX test values. The 50 ft wayside measurement can also be approximated by subtracting 30 dBA from the OBSI measurement.

The OBSI system promoted by Caltrans used the original GM fixture and typically tested with one tire; specifically, the Goodyear Aqua Tread 3. Various tires have and continue to be tested but the Goodyear has bee the primary test tire.

Comparison of OBSI and CPX Data

Caltrans and the Arizona Department of Transportation (ADOT) jointly researched the comparison of the OBSI and trailer based CPX system. The data presented in Figures 4 and 5 were obtained using ADOT's CPX trailer with both the SPL and SI systems installed on the same wheel. This eliminates any temperature difference or tracking differences. The data was collected at the exact same instance and location. The initial on-road results comparing overall A-weighted levels (500 to 5000 hz) for the CPX trailer and OBSI are provided in Figure 4. These results indicate a linear offset between the data in which the OBSI data is 3.5 dBA higher than the CPX data. Figure 5 gives a typical comparison of the spectrums obtained from the two systems. Again, it is evident there is good agreement between the techniques. Additional testing will be conducted between the ACPA OBSI system and the MTQ CPS system.

ACPA OBSI Testing

In 2006 ACPA will be improving its tire-pavement noise measurement capabilities. The current system is based on General Motor's original design that uses the OBSI measurement procedures. The planned improvements for 2006 include changing to a different test tire and doubling the number of microphones used for data collection. The Goodyear Aqua Tread tire was discontinued approximately 1 ½ years ago and it will now be necessary for users to upgrade to another standard tire. A similar problem exists in Europe with the draft ISO Close Proximity method (e.g. CPX) where most of the European standard tires are no longer produced. As such, both the US and European tire-pavement noise testing communities are considering the new ASTM **S**tandard **R**eference **T**est **T**ire (e.g.SRTT) (E1136-Draft) as one of the new standard tires. This tire is already used by the vehicle manufacturers for testing purposes and is currently used as the standard tire for profile measurement. The new ASTM test tire is a 16-inch tire size (e.g. P225/60R16), which better represents the increasing wheel size used on today's passenger cars. The previous Goodyear OBSI test tire was a 15-inch tires size (e.g. P205/60R15). Both tires are shown in Figure 6. The new ASTM SRTT will be produced for the next ten years using the exact same composition and tread design and this will prevent it from being discontinued or modified as can happen with standard commercial tires such as the Goodyear tire.

The ACPA has also upgraded its two microphone systems to a four microphone system. This allows the data to be collected in one pass instead of two, significantly increasing test efficiency. It also allows the leading and trailing edge positions to be tested at the same time eliminating lateral tracking and temperature differences. Figure 7 indicates the new ACPA four microphone based fixture which can be compared to the original GM design indicated in Figure 3.

To analyze data from the four microphones, the ACPA will be using Bruel & Kjaer's PULSE analyzer and software. This system provides additional benefits as it directly stores the wave file to disk simplifying the data collection process and also allowing additional analysis features.

The development of the improved ACPA OBSI system was a joint venture between Caltrans, ACPA national staff, and the Canadian Cement Association (CAC). ACPA staff provided the labor and fixture development, Caltrans conducted the initial validation research and the CAC provided the resources to improve the system and to bring it on line. All three organizations participated to improve the system. The improved system will raise the bar for increased productivity and more convenient OBSI testing. Several two probe systems are already in development and an OBSI users group has already been formed to share experiences and information.

An FHWA/AASHTO Expert Task Group is currently drafting a standard for the measurement process, referred to as On-Board-Sound –Intensity (OBSI). It is anticipated that this draft will be submitted for AASHTO review and consideration during 2006.

Establishing Existing Acoustic Performance

In the development of quiet PCCP surface textures it is first necessary to establish the performance of traditional textures over their acoustic life. This provides assessment of the current technology and potentially some options for improvement. Figure 8 indicates the reported results to date regarding the authors knowledge of the represented textures. By examining Figure 8 it becomes readily apparent which textures provide the quieter surfaces. The transverse textures, particularly the random transverse are unusually loud. Since these were the main textures used for most of the existing US pavements it is not surprising that complaints exist. The drag textures and diamond ground surfaces appear to be the quietest of the conventional surfaces. Porous pavement is the quietest texture and the only surface currently known to test below 100 dBA. However, it is not a conventional texture. The results presented in Figure 8 were obtained with OBSI equipment using the Goodyear Aqua Tread passenger car tire at a test speed of 60 MPH.

Currently, the ACPA is involved in three different research efforts to develop an improved surface. These projects are the FHWA/ACPA/ISU Surface Characteristics Study, the Purdue TPTA Study and the ACPA OBSI field measurement program. The Purdue Tire Pavement Test Apparatus (TPTA), shown in Figure 9, is the innovative workhorse. This system, since it is laboratory based, provides the opportunity to test surface textures that may be difficult or risky to construct in the field. As such this allows for a complete understanding of fundamental mechanisms involved in the tire/pavement interaction. However, since it is laboratory based, the relationship to actual field performance needs to be verified. The TPTA only tests to 30 MPH and cannot traffic textures as would normally occur in the field. That is, in the field, once the project is finished the traffic wears down the texture somewhat. It is extremely difficult to simulate this under laboratory conditions.

The laboratory testing will first evaluate diamond ground surfaces, then the effect of joint width and offset on noise measurements, and finally truly innovative surface textures will be evaluated. Figure 10 & 11 indicated the grinding head that was constructed for the TPTA and resulting ground surface. Early results from this work, shown in Figure 12 indicated that an approximate 2 dBA reduction in noise level was achieved after the first attempt at fin breakage.

This work suggested that the resulting fin profile was the important variable to control, and subsequent research will employ chopper blades in lieu of conventional spacers in an effort to produce a constant fin profile. This testing is currently underway and results are not yet available. Figure 13 is a photo of the chopper blade arrangement next to a conventional diamond grinding arrangement.

The second major research effort is the FHWA/ACPA/ISU study that is a long term program designed to produce the final answer. Three different types of projects are utilized; (1) newly constructed projects where extensive testing can be accomplished prior to opening to traffic and at periodic intervals thereafter, (2) recently constructed projects that can provide early test results from previously existing projects, and (3) older projects that can provide insight into long term performance. For the Type 1 & 2 projects data collection consists of profile, texture, noise, and friction measurements. For the type 3 projects only texture and noise are evaluated. The major thrust of this effort is to establish the surface variability, both in the construction phase and in the resulting performance, and to develop relationships between texture measurements and noise and friction.

Results to date from this study suggest considerable variability within short pavement sections, and that controlling this variability is critical to developing quieter concrete pavements. Figure 14 indicates the preliminary test results obtained on the first Type 1 test sections. The yellow dot indicates the mean OBSI test value for the section and the blue dots indicated five foot moving averages. As evident, there is considerable variability within each surface type with random transverse tining indicating the largest variability. The numbers within the yellow dot indicate the rank order of the treatments.

One of the unique aspects of the FHWA/ACPA/ISU project is the measurement of the 3-D texture using the Robotec shown in Figure 15. This device allows continuous measurement of surface texture enabling direct comparison of texture measurements to noise and friction. A typical surface texture plot is shown in Figure 16. This is a plot of a longitudinally tined PCCP surface.

ACPA OBSI Testing

The third research program is the ACPA in-house OBSI program intended to provide acoustic performance over time data and to provide troubleshooting capability. Although it is unlikely that concrete textures change appreciable over time, little data exists to support this claim. Therefore it is necessary to develop sufficient data for each of the texture categories to be able to properly account for the acoustic performance in such models as TNM.

Summary

To develop quieter concrete pavement surfaces it is necessary to understand the performance of existing textures, to be able to control construction variability, and to implement textures which promote reduced noise levels while maintaining existing safety and friction levels. The current approach to this is to use the Purdue TPTA as the test bed for evaluating innovative solutions, then full scale field test sections. Field evaluation will be conducted using the OBSI systems that are gaining in popularity in the US.

Current knowledge suggests that for transverse tined surfaces, increasing tine spacing and tine depths increase the overall noise levels. So by simply paying attention to these factors, significant improvements in noise levels can be obtained. For new construction, longitudinal tining and astro-turf drag textures are seeing more use in the US. Diamond grinding on both new surfaces and existing surfaces also provides a quiet surface.

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Tables

TABLE 1: PCCP Surface Locations Used in FHWA REMEL Development for Continuous Flow Data

State	Route	Assumed Texture Type	Pavement Age (yrs)	Roadway Grade
CA	I-580	Longitudinally Tined	8	3%
CA	I-5	Longitudinally Tined	4	0%
CA	I-15	Longitudinally Tined	24	5.6%
CA	I-15	Longitudinally Tined	25	4.5%
MD	140	Burlap Drag	43	0%
MD	I-495	Burlap Drag	39	0%
MI	I-94	Transverse	3	0%
TN	I-65	Burlap Drag	39	0%

Table 2: Comparison of Average Pavement Type Emission Levels to Specific Pavement Type (dB)

Pavement Type	Automobile	Medium Truck	Heavy Truck
Dense Graded AC	-0.65	-0.64	-0.59
PCCP	2.36	1.47	0.72
Open Graded AC	-2.20	-1.15	-1.66

Figures

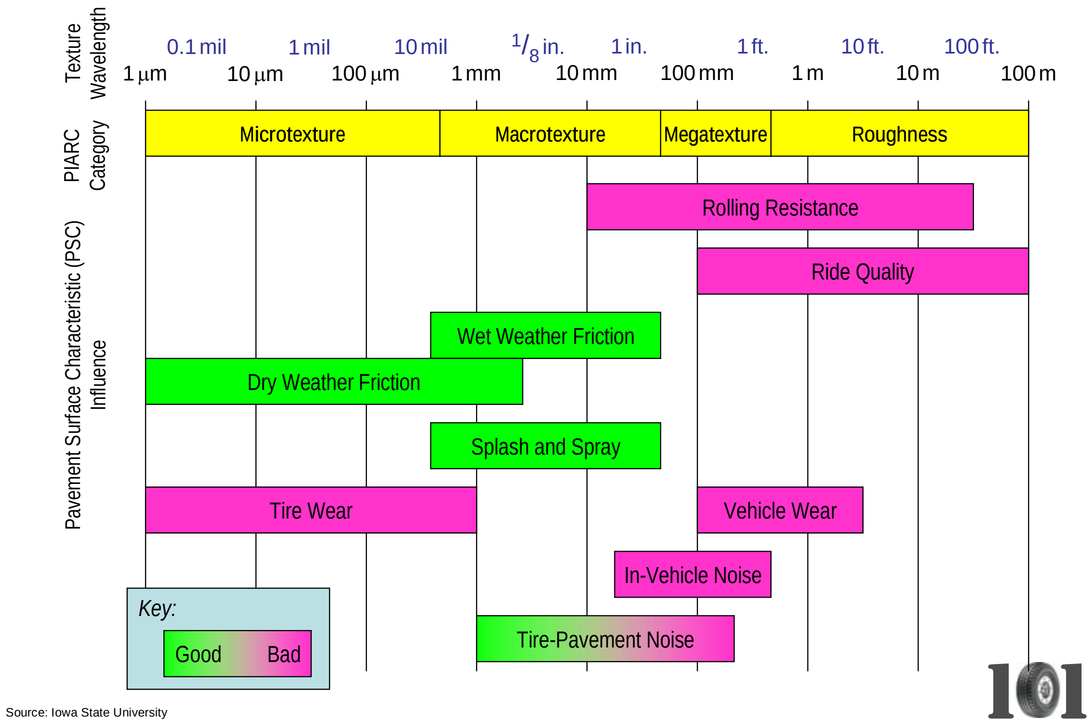

Figure 1: Pavement Factors Relating to Texture

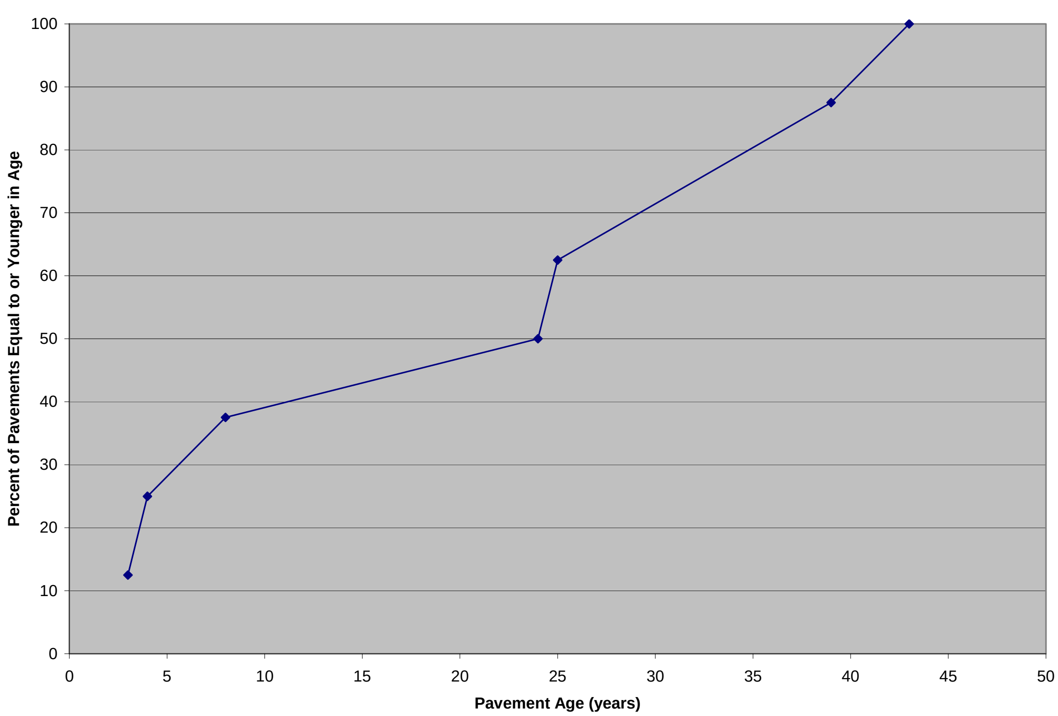

Figure 2: Cumulative Frequency Distribution Plot of Pavement Age Used in Continuous Flow REMEL Study for PCCP Test Sites

Figure 3 General Motors OBSI Apparatus

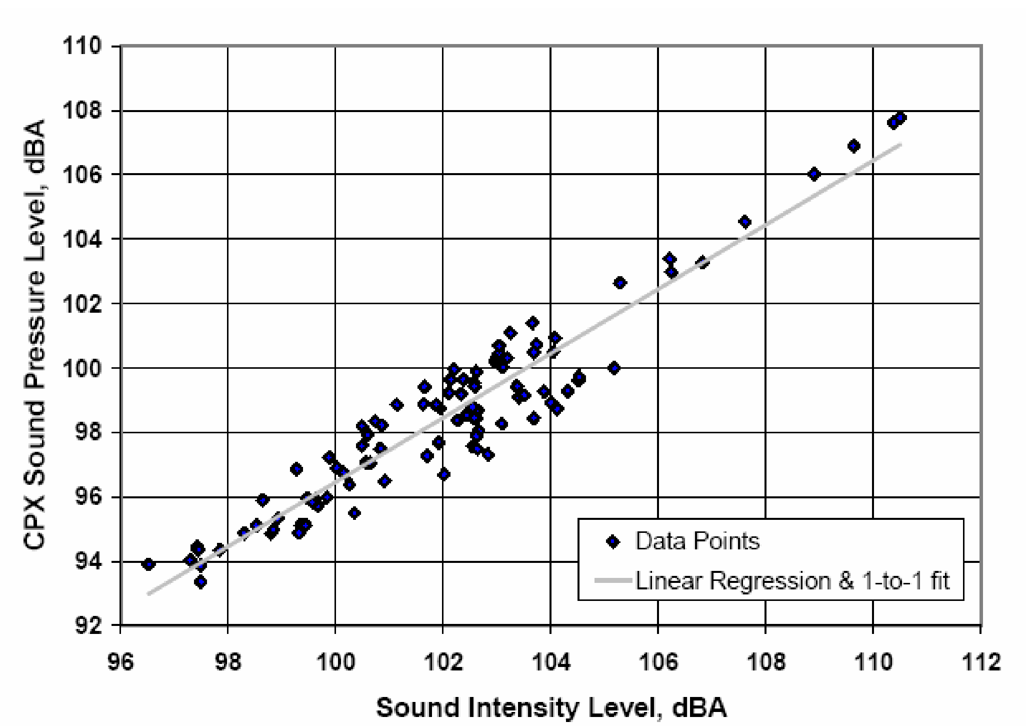

Figure 4 Comparison of Tire/pavement Noise Source Levels Measured with Sound Intensity and CPX Methods for One Tire on Multiple Pavement Types

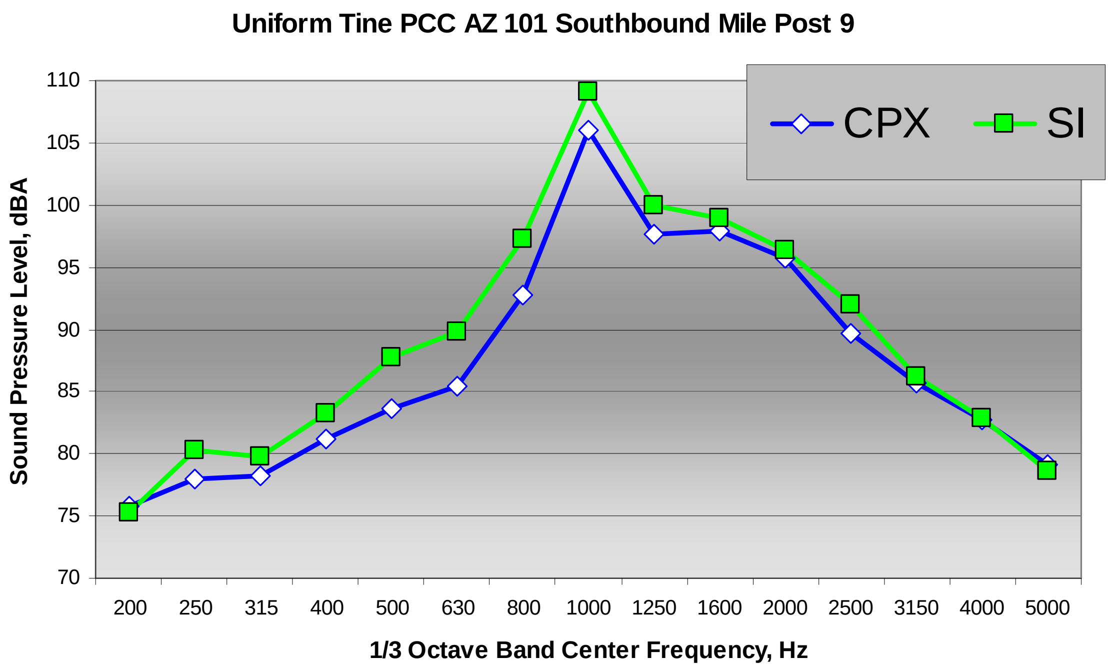

Figure 5 Comparison of OBSI and CPX Spectrums

Figure 6 Comparison of Goodyear Aqua Tread (left) and ASTM SRTT Tires (Right)

Figure 7, ACPA Single Pass OBSI Apparatus

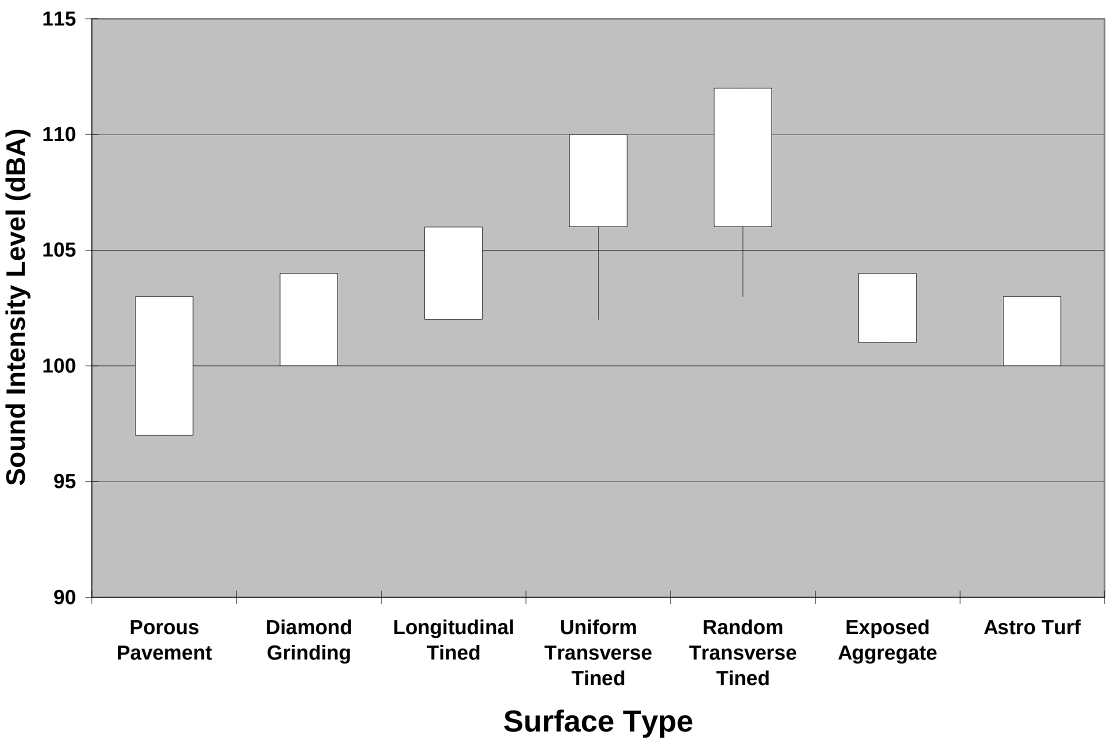

Figure 8 Range of Expected Noise Levels for Selected Pavement Textures

Figure 9 Purdue Tire Pavement Test Apparatus

Figure 10 Grinding Unit Attached to TPTA with One Wheel Track of Blades Attached

Figure 11 Close Up of Texture Resulting from Diamond Grinding

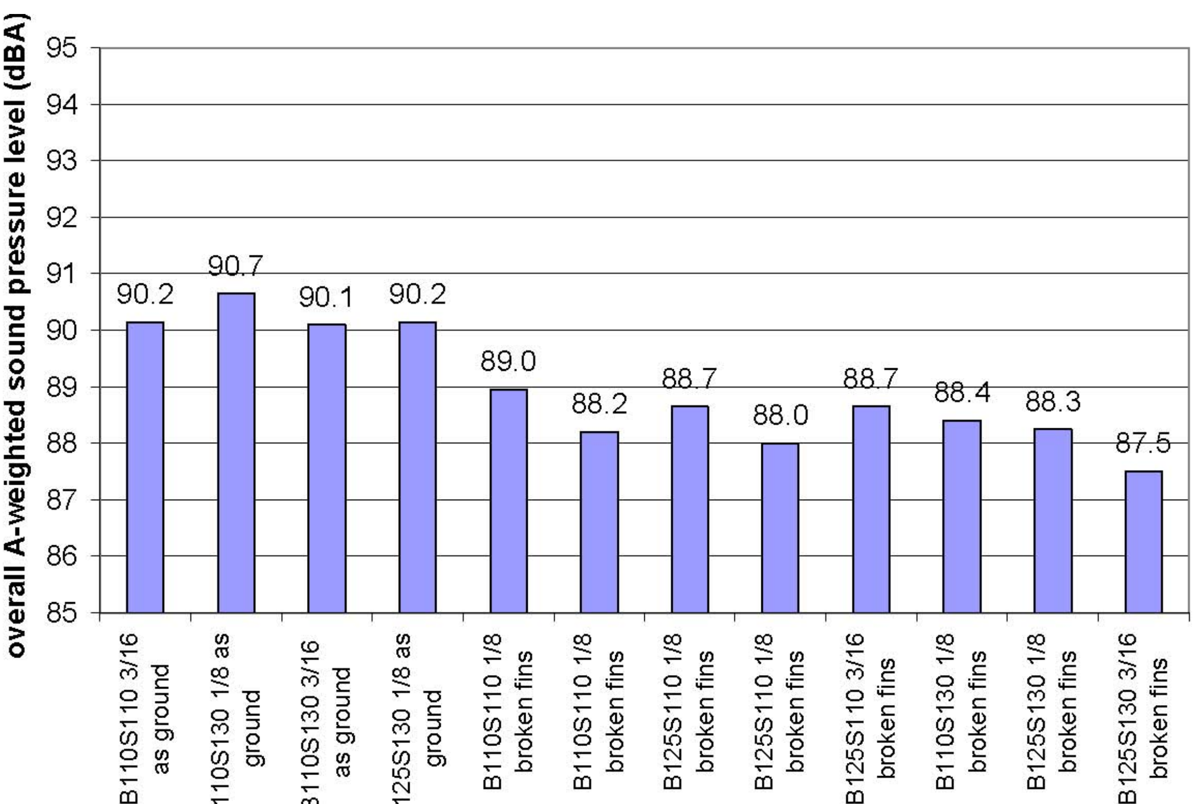

Figure 12 TPTA SPL Before (left half) and After (right half) Results from Mechanically Breaking Fins

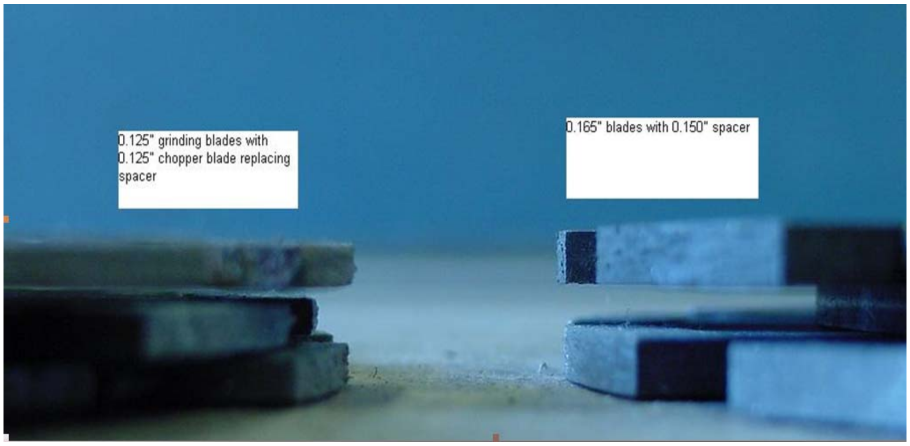

Figure 13 Photo of Chopper Blades and Conventional Spacer in Diamond Grinding Operation

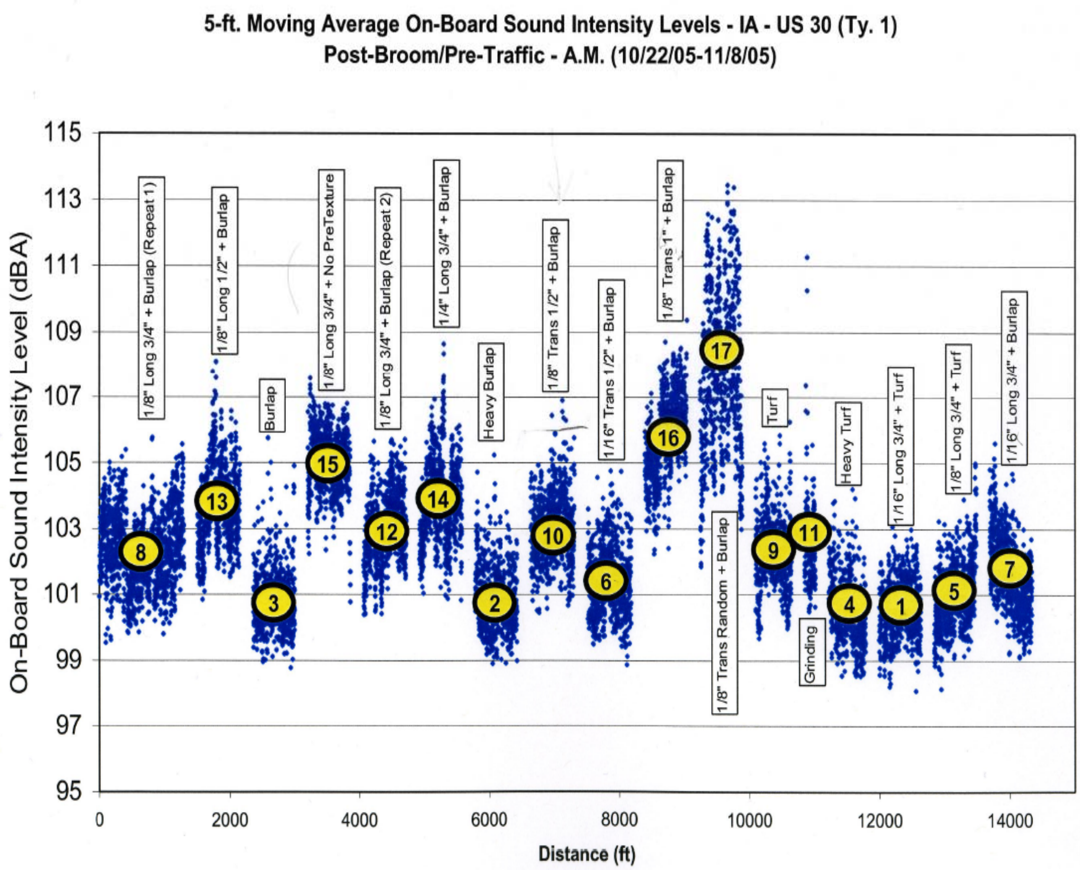

Figure 14 Five Foot Moving OBSI Averages for US 30 Test Sections [10]

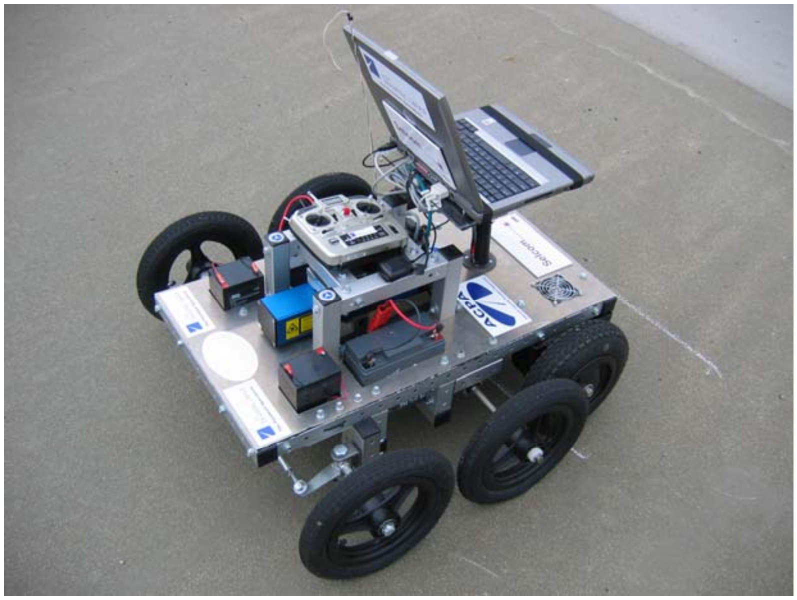

Figure 15 Photo of Robotec 3D Texture Measurement System[10]

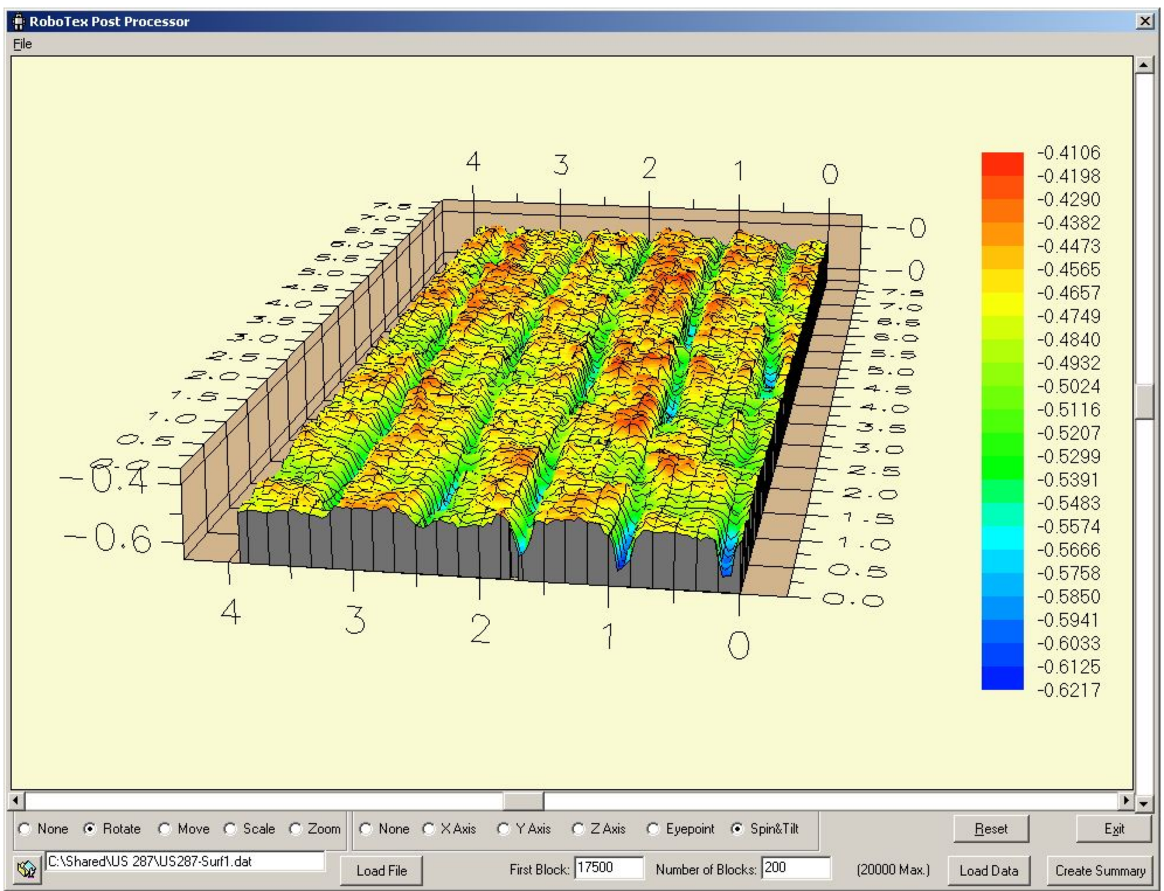

Figure 16 Graph of 3-D Texture Measurement Results Obtained Using Robotec Device[10]