Safe, Smooth, and Quiet Concrete Pavement

Larry Scofield
American Concrete Pavement Association, Mesa, Arizona, United States

ABSTRACT

The concrete industry has been conducting research since 2005 to evaluate new and innovative textures in regards to tire-pavement noise generation and has developed a new pavement surface for testing and evaluation. The new surface, called the Next Generation Concrete Surface (e.g. NGCS) was developed through research at Purdue University using their Tire Pavement Test Apparatus (e.g. TPTA). To date, seven test sections have been constructed in five states in the United States.

The NGCS test pavements have proven to be quieter than conventional diamond grinding (e.g. CDG) at the time of construction and may offer a slight advantage regarding acoustic durability. Since this is a recently developed product, the costs are higher than for CDG and the cost-effectiveness is still being evaluated.

This paper presents the findings of the research focused on the development of the NGCS and the NGCS LITE. The NGCS LITE texture, constructed in the fall of 2008, is a diamond ground technique to impart additional micro-texture to the lands of an existing NGCS texture. This process provides an economical means for re-establishing micro-texture should it become necessary. It essentially allows construction of a perpetual surface texture (e.g. PST).

This paper reports on the development process and the field trials that have been constructed and monitored since 2007. In addition, the paper presents a historical perspective on the development of diamond grinding/grooving in California.

KEYWORDS

PCCP, Quiet Pavement, Texture, Friction, Noise

HISTORICAL DEVELOPMENT OF DIAMOND GROOVING AND DIAMOND GRINDING TEXTURES

Introduction

Although diamond grinding was first used in the United States to smooth a runway at an air force base in Arizona in the 1950s, most of the initial development of diamond grinding and diamond grooving occurred in California in the early 1960s. The initial development occurred first for diamond grooving, which was developed to restore frictional properties to older concrete pavements. This development was championed by the California Department of Transportation in the Los Angeles Area.
By the early 1970s the Los Angeles Freeway system was experiencing the wear from 40 million vehicles per day\textsuperscript{2}. The high traffic volumes were causing increased wearing of the texture of the concrete roadways and it had been observed for many years that friction was being reduced, particularly in the travel lanes of the roadways.

**Development of the California Friction Procedures and Requirements**

During the period between 1950 and 1958, Professor Moyer of the University of California conducted skid testing of a large number California pavements using a towed skid trailer device\textsuperscript{3,4}. On the basis of that work it was concluded that a minimum friction value of 0.025 was sufficient\textsuperscript{5}. It was also concluded that the lowest skid value for any given surface would be attained when the brakes were locked on a vehicle having a smooth tire on wet pavement traveling at approximately 50 mph.

In the late 1950s, John Skog of the California Division of Highways and Materials Research Department developed the California Skid Tester (See Figure 1).\textsuperscript{2} The CT-342 friction tester is unique in that it uses glycerin as the lubricating fluid between the tire and the roadway surface instead of water. The test consists of spinning the wheel up to 50 mph while supported above the roadway and then dropping it to the pavement with no additional power provided to the wheel. The distance the wheel travels before coming to a stop is a measure of the pavement friction. The equipment converts kinetic energy to potential energy. Although the device can easily be transported in the back of a pickup truck, the device operates at a fixed location while testing.

This device was used for investigations of pavement friction and to test new construction. Testing between the Moyer trailer and the California device were conducted to develop a correlation between the two devices and the extensive research conducted by Moyer. A coefficient of friction of 0.30 tested using the CT-342 device was equal to a towed trailer skid number of 40 (e.g. SN40)\textsuperscript{2}.

In addition to establishing correlations to the Moyer research, California attempted to establish CT-342 correlations to work conducted by C.G. Giles in England and T.E. Shelburne in Virginia\textsuperscript{4}. Since the Giles work was conducted with a British Portable Tester (BPR), California purchased one and developed a correlation to the California Tester (e.g. CT-342). The Virginia research, which used a skid car, had already been correlated to the BPR and therefore California could correlate to both studies on this basis.

Figure 2 indicates the minimum friction values reported by England, Virginia, and California.
The analysis led California to conclude that pavements exhibiting a minimum California tester value of 0.3f were satisfactory. In addition, testing conducted in England and Virginia, which both experienced higher levels of rainfall, indicated that a California friction test value of 0.28f should be satisfactory for all locations except possibly curves. This also correlated well with work conducted in Florida and other work in Virginia. Subsequent investigations using the California Tester at locations where wet weather accidents occurred indicated the average friction value at these sites was 0.22f. None of the accident sites achieved a friction value as high as 0.28f. Caltrans still considers a friction value of 0.3 as the minimum acceptable level on their roadways.

In the fall of 1969 California initiated a statewide pavement friction surveillance inventory. This testing was conducted with the General Motors skid trailer and supplemented with a Soil Test Skid Trailer. The inventory program was designed to assist the engineers with determining the need for frictional improvement and in determining rates of wear.

New concrete pavements at that time reported SN40 values of 50-55. After five years of heavy traffic on Interstate 605, for example, the skid number of the median lane tested at 38 while the travel lane tested at 25.
Development of the California Diamond Grooving Procedures and Specifications

Overview

Providing and maintaining skid resistance surfaces are important considerations for California. Early friction testing indicated that all types of pavements eventually show some reduction of friction during their service life. This was attributed to wearing and polishing caused by traffic. It was noted that some sections of concrete pavements, especially on curves, were incurring an unusual number of wet weather accidents. After considering the use of acid treatment on the surface or the application of a coal-tar epoxy screening seal coat, it was decided to study the effect of grooving the concrete. Most all of California’s grooving research was conducted on grooving in the longitudinal direction. This was due to the belief that this provided better lateral stability.

The various types of grooving patterns will be discussed in greater detail in subsequent sections, but to summarize, the most common type of grooving pattern was rectangular in form and was varied in depth, width, and spacing. Other types consisted of rectangular shaped grooves but the bottoms and the edges at the pavement surface were partially rounded. Others had a large V cut separated by smaller V cuts. A number of different patterns were evaluated in order to determine the increase in friction factor, wear resistance, and possible handling issues. Figure 3 indicates the effect of grooving on the coefficient of friction for various concrete pavement projects and grooving patterns.

As indicated in Figure 3, most all of the grooving patterns significantly improved the friction level. Beyond that however, it is difficult to establish a clear winner. For example, the 1/8” by 1/8” inch grooves spaced on 1” centers have the two smallest improvements and one of the largest improvements. The same pattern placed on ½ centers provided the most consistent results but only three data points exist. The Christensen surfaces provided two of the largest improvements.

A very important characteristic of any treatment intended to raise the existing friction level is the resistance to wear and polishing. This was also evaluated by California and the changes in friction level over time are indicated in Figure 4. Although at the time of the original report, it was concluded that insufficient time had occurred to draw firm conclusions; it appeared that the nature of the aggregate and mortar strength may influence the resistance to wear and polishing of the grooved areas.

A before and after accident study of the early grooving projects indicated that total accidents were reduced 62 percent and wet weather accidents were reduced 90 percent.

Groove Pattern Evaluation

Although there is no good record of what groove patterns were used where, there is evidence of a 1/8” by 1/8” groove configuration (depth unknown) on a 1963 and 1966 project. There is also evidence of the same groove width used on ¾” spacing on a different 1966 project. The earliest reported major project with grooving is I-5 near Los Angeles in 1961. It appears that groove spacing and depth were being varied from project to project during its early use. The current grooving specification was first required in the specifications in 1969. The 1969 specification required that grooving blades shall be 0.095-wide and spaced on ¾ centers. Grooves were to be not more than ¼” deep nor less than 1/8” deep. This requirement is still used today. Most grooving prior to the 1969 specification requirement involved the use of 1/8 inch wide grooves.
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Figure 3. Effect of Grooving Pattern on Average Coefficient of Friction on Concrete Pavements

Friction Evaluation of the Grooving Patterns

The earliest reported groove pattern friction testing was October 8, 1962 on the northbound center lane of the El Cerrito Overpass. Six different rectangular grooving patterns were cut into the deck. The grooves were all 1/8 inch wide but two depths; 1/16 inch and 1/8 inch and three blade spacings: 1 inch, 1/2 inch, and 1/4 inch were used. Friction measurements obtained during 1962 did not demonstrate a superior pattern.

The next reported groove pattern friction evaluation was conducted as a laboratory experiment. Two five feet by fifty feet test slabs, 0.3 feet thick, were poured on the ground at the Materials and Research Laboratory of the California Division of Highways in November of 1967. The mix was a six sack mix, two inch slump transit mixed concrete, with one inch top size aggregate. One slab was given a smooth trowel finish and the other a burlap drag texture. Both slabs were cured using pigmented curing compound as was typically used on paving projects. In February of 1968 California friction testing was conducted on each of the slabs prior to constructing the grooving experiment. In March of 1968 six different grooving patterns were cut into each of the test slabs with a Christensen Concrete Planar as indicated in Figure 5. As indicated there were three Christensen patterns evaluated as shown in Figure 6.
The results of this experiment are indicated in the abstract from the original report as follows: “Six different grooving patterns; 1/8 by 1/8 inch rectangular grooves spaced at 1/2, 3/4 and one inch centers and the number 6, 7 and 15 patterns of the Christensen Diamond Services Company were cut in each of two PCC test slabs. One slab had a trowelled finish with an average initial coefficient of friction of 0.14 as determined by the California Skid Tester. The other slab had a burlap drag finish with an average initial coefficient of friction of 0.35. Higher coefficients of friction were obtained with the Christensen grooving patterns than by the 1/8 by 1/8 inch rectangular grooves. The frictional properties of the burlap drag finish were unchanged by the 1/8 by 1/8 inch rectangular grooves. Longitudinal coefficient of friction measurements were quite erratic for the three 1/8 by 1/8 inch rectangular patterns which were cut in the trowelled PCC surface and very little improvement in frictional properties were obtained.

Friction measurements measured at 15 to 45 degrees to the direction of the grooves were much more consistent, and are probably more representative of the actual improvement in the frictional properties of the surface. This is caused by the small contact area of the tire used on the California Skid Tester which may touch as few as 2 grooves during a longitudinal test with the grooves spaced at one inch. If 1/8 by 1/8 inch rectangular grooves are used, the most improvement in skid resistance is provided by the 1/2 inch center to center spacing.”

Figure 4. Change in Friction Values Following Grooving of Concrete Pavements

![Graph showing change in friction values following grooving of concrete pavements.](image-url)
The third California friction study was reported in 1974. In order to measure the change in friction of diamond grooved pavements, 125 test sections were established in the Sacramento area and 118 in the Los Angeles area. In the Sacramento Area the average skid number increased from 40 to 44 as a result of the grooving. In the Los Angeles Area the skid numbers increased from 33 to 41. The reported skid numbers were based upon the locked-wheel skid tester. The study reported that these marginal increases in friction values were not consistent with the dramatic reductions in wet weather accidents that are reported with the use of longitudinal grooving. The following reason was given for this: “It is believed that grooves provide a skidding accident reduction through their resistance to lateral skidding. Since the skid test trailer is designed to measure only longitudinal skidding, the skid number obtained cannot reflect this property. Also, this and other data indicate that skid number is only one of many characteristics of a roadway that contribute to accident frequency. Thus it is unlikely that a definitive correlation between accident frequency and skid number would exist.”
One concern that was encountered with the advent of roadway grooving was the lateral stability issue that was presented by light cars and motorcycles at the time. Various reports indicated that the grooves would result in loss of control by drivers of motorcycles as a result of the tire-pavement interaction. Three studies were reported between 1966 and 1969 to investigate this. The first two studies, conducted in 1966 and 1968, indicated that the 0.095 blade width provided a groove pattern which was the least objectionable to motorcyclists. These first two studies have not been located except for their discussion in reference 6. Reference 6 indicates that the test drivers in the 1968 study felt they had better stability at 60-80 mph when riding over the 0.095 inch groove width than over smooth surface streets. The third study, conducted in 1969, reported results contrary to the 66 and 68 studies indicating the 1/8 inch groove width was preferred.

The reason for selecting the 0.095 blade width for the 1969 specification on longitudinal grooving has been reported as follows: “Our earlier grooving projects used a 1/8 inch wide blade for cutting the grooves. However, there is a tendency for the grooves to widen out on small radius curves with high super elevation. As the groove widens, the “tracking” effect increases and the skittering effect is felt by drivers, particularly motorcyclists. In an effort to reduce these effects, a cutting blade of 0.095 in. width is now specified.” Reference 2 also indicated that groove depths over 1/4, may produce spalling between the cuts.

Driver Evaluation of Grooving Patterns

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In 1969 the California Public Works Department, Division of Highways constructed a diamond grooving experiment on an old concrete pavement to determine if the safety of the motorcyclist was affected by grooving concrete pavement, and if the sensitivity to selected grooving patterns could be determined. At the time, diamond grooving roadways for safety was increasing in use and there were reports that certain grooving patterns resulted in riding sensations to the motorcyclist which were different from those experienced on un-grooved pavements.

The six test sections were constructed on County Road 32A which was constructed in the 1940s. This section of highway had been replaced by the construction of I-80 in the mid 1960s and the California Public Works Department subsequently relinquished the roadway to the County and it was renamed County Road 32A.

The six grooving patterns selected represented the most commonly used diamond grooving patterns in use in California at the time and are indicated in Figure 7. The grooving patterns studied were the Christensen No. 15 and Type A, and the 1/8” by 1/8” groove spaced at ½, ¾, and 1 inch centers, and the 0.095 blade width spec spaced at ¾”. The results of that study concluded that there was not a safety issue with any of the patterns.

**DIAMOND GRINDING**

Diamond grinding, like diamond grooving, had a lot of its early development influenced by California. Unlike, diamond grooving however, there does not appear to be a lot of reported studies on experimentation. The equipment and blades have improved significantly from the early days but the same 1/8 inch blade widths are still commonly used.

The first concrete interstate rehabilitation project was constructed in California in 1965. After approximately 19 years of service and a traffic load of over a billion vehicles, Interstate 10 (the San Bernardino Freeway) east of Los Angeles, was showing signs of age. But instead of resurfacing the concrete road with conventional methods, California highway engineers experimented with a totally new concept- diamond grinding. Small and, by today’s standards, simple machines equipped with diamond saw blades ground 1,008,000 sq. ft. of concrete. The result was a level and textured finish conforming to state specifications for new roads as shown in Figure 8. That same section of structurally sound concrete road got its third lease on life, when the California DOT did a third diamond grind of the project. This section of highway is still in use today.
DEVELOPMENT OF THE MODERN DAY DIAMOND GRINDING SURFACES

Introduction

In 2005, the ACPA contracted with Purdue University to conduct surface characteristics research. This project was a combined effort between the Portland Cement Association (PCA), ACPA, and the International Grooving and Grinding Association (IGGA). The study focused on three areas of research; diamond grinding, joint slap effects, and innovative new textures.

Next Generation Concrete Surface (NGCS)

The Purdue research indicated that noise levels of the diamond ground textures was not a function of the blade or spacer widths, but instead was a result of the fin (land) profile. The more consistent the fin profiles the lower noise levels achieved, independent of the spacer or blade width. With this new knowledge, a texture was developed that controlled the resulting fin profile with the objective of producing minimal positive texture. This new surface was eventually called the Next Generation Concrete Surface or NGCS.
Purdue Tire Pavement Test Apparatus

Purdue University’s Herrick Laboratory conducted the research using their Tire Pavement Test Apparatus (e.g. TPTA). The TPTA, shown in the right-hand side of Figure 9, consists of a 38,000-pound, 12-foot-diameter drum that makes it possible to test numerous types of pavement textures and compositions in combination with various tire designs. Six, curved test-pavement sections fit together to form a circle. Two tires, mounted on opposite ends of a beam, are then rolled over the test samples at varying speeds while microphones and other sensors record data. As indicated in Figure 9, two wheel tracks were constructed on each of the six curved test panels allowing 12 surface textures to be tested in one setup. Speeds between 0-30 MPH can be tested and test temperatures ranging between 60-80 degrees are possible.
The left hand side of Figure 9 indicates the diamond grinding head that was constructed by Diamond Surfaces, Inc of the IGGA. This head was used to grind all the surfaces studied. It produces an 8 inch wide diamond ground surface. Typical diamond grinding units grind 3 ft and 4 ft wide paths and use 50-60 blades per foot. To fully "stack" a head with new blades can cost $50K, and take 6-8 hrs of time. The use of a small, 8 inch-wide head, tremendously reduces the blade cost and set-up time. When comparing different grinding blade/spacer configurations, this is a very important consideration. The grinding unit replaces one of the wheel set ups as indicated in Figure 9. Once the surfaces are diamond ground, the unit is removed, the test wheel apparatus re-installed, and testing is conducted.

The Purdue TPTA was the innovative workhorse for the PCA/ACPA/IGGA surface texture efforts. This device allows textures to be produced and tested that may not currently be possible to construct with present day equipment. Additionally, testing can be accomplished without requiring traffic control or endangering workers or travelers.

**TPTA Measurement Systems**

Figure 10 indicates the OBSI equipment used to measure tire-pavement noise and the RoLine laser used to measure texture profiles. As indicated in the left-hand side of Figure 10, the OBSI equipment was mounted to the test tire support frame. Since two tires are used during testing, it was possible to test with two different tire types at the same time.

The right-hand side of Figure 10 indicates the texture measurement system. Texture measurement was accomplished by removing one of the tire support frames and installing an arm to support the RoLine sensor.
Comparison of Conventional Diamond Ground Texture to NGCS

The left photo in Figure 11 indicates a close up photo of the fin profile just after grinding and before any fins are knocked down due to traffic and winter maintenance operations.

As evident in the photo, the harder aggregate stand “proud” in relationship to adjacent areas. Purdue indicated that it was probably this variability in fin profile that affected the tire-pavement noise generation. Textures with low variability were quieter than textures with high variability. In conventional diamond grinding, the resulting fin variability is influenced by the blade/spacer configuration, the concrete mixture, aggregate type, pavement condition, equipment set up, etc. This makes it very difficult to control from an experimental standpoint. Once traffic and winter maintenance operations break down the fins the conventional diamond grind texture appears as indicated in the right photo of Figure 11 with more uniform fin profile.

To evaluate this hypothesis, it was decided to produce a texture with essentially no positive texture. That is, the surface would be diamond ground smooth and then additional texture imparted by grooving. In this manner, the exact fin profile could be controlled/anticipated at the time of production, unlike conventional diamond ground (CDG) surfaces which are affected by many variables. Figure 12 indicates the NGCS surface. It should be noted that the CDG surface shown in Figure 11 produces texture in the upward or positive direction while the NGCS surface produces texture in the downward or negative direction. The Purdue texture, later called the Next Generation Concrete Surface (NGCS) was desirable from the standpoint that it was more of a “manufactured surface” and thus could be controlled as necessary.
Evaluation of the Noise Levels for Field Test Sections

NGCS Noise Results (Minnesota and Illinois)

NGCS surface test sections have been constructed in five states to date; Minnesota, Illinois, Wisconsin, Kansas, and Oklahoma. Two more test sections are scheduled for construction in 2010. To date, the Minnesota (I-94), Illinois (I-355), and Kansas (I-70) are the only sections that have been tested so far.

Figure 13 indicates the OBSI levels for the first two field test locations (e.g. I-94 and I-355). Both sites had received approximately five months of traffic at the time of testing. The conventional diamond grinding (e.g. CDG) is indicated in light green and the NGCS sections indicated in dark green. For each location and surface type, the oldest test result is displayed to the left of the most current result. The I-94 sections are indicated in the left half of the Figure and the I-355 sections in the right half. The results shown are the average of three tests for each surface type. Figure 14 indicates the spectral results for both locations.
As indicated in Figure 13, the I-355 CDG and NGCS sections were only 0.2 dBA different in level at the November 2007 testing with the NGCS being quieter. During the May 2008 testing both surfaces produced similar results. The NGCS tested approximately 0.4 dBA louder in May than the November measurements, while the CDG tested 0.2 dBA louder. These differences are probably within the test repeatability of the OBSI equipment.

When reviewing Figures 13 and 14, there are a number of things to note: (1) As evident in Figure 6, the NGCS frequency pattern is slightly different than the CDG.
The NGCS has a characteristic dip at 1600 Hz and is typically lower in level at all frequencies below this dip and higher in level at all frequencies above the dip. (2) The overall level of the CDG and NGCS are more similar in the trafficked condition than in the as-constructed condition. This is a result of the wearing down of the CDG fins (see Figure 11). (3) The NGCS has produced more consistent results. That is, they are essentially at their final noise level at the time of construction and do not have to wear away to a “finished level”.

It should be noted that the I-355 sections used ¾” center to center groove spacing instead of the ½” center to center spacing developed at Purdue. This was to accommodate the use of the same grooving equipment that was used to construct the longitudinally grooved turf drag.

**Minnesota NGCS and NGCS LITE Noise Results (2009)**

In addition to the NGCS surface a NGCS LITE texture was developed to provide a means for producing a renewable surface texture for the NGCS. Since the NGCS texture employs very wide lands as indicated in Figure 12, it is possible to very efficiently texture just the lands. For pavements without faulting this can be accomplished very cost effectively. Only one section of the NGCS LITE has been constructed to date. This section was constructed in the fall of 2008. Testing of the I-94 test sections was recently accomplished and the results are indicated in Figure 15. As indicated, the NGCS LITE and NGCS texture produced similar results and were approximately 1 dBA less than the conventional diamond ground surface. The 2009 results are slightly higher than the 2008 readings for both the CDG and the NGCS sections. Due to the development of a pot hole in the right wheel path, testing had to be shifted to the left side of the lane. The effect of this shift cannot be taken into consideration at this time.

![Figure 15. Minnesota I-94 2009 Test Section Results](image-url)
Kansas NGCS and Other Texture Noise Results (2008)

In support of the European long life pavement scan, there was a renewed interest in two lift pavement construction and exposed aggregate surfaces. In response to this interest, KDOT constructed a project using the two lift technique and allowed several texture experiments to be constructed on the surface. Figure 16 indicates the noise level results for those test sections tested at the time of construction and before the roadway was opened to traffic. As indicated, the NGCS was the quietest of the surfaces placed and the exposed aggregate was the noisiest surface placed.

![Figure 16. OBSI Levels for the Kansas I-70 Surface Test Sections at the Time of Construction](image)

**Friction Performance Testing**

The friction performance of the MnROADs I-94 test section has been monitored by MnROADs since the construction of the test sections. Figure 17 indicates the time series behavior of the sections for both the ASTM ribbed (E501) and smooth (E524) tires. It should be noted that I-94 was closed to traffic on 4/2/08 to allow construction of new test sections on the facility. So there is approximately five months of interstate traffic on the test sections. The “traffic” occurring after the measurements obtained on 5/28/08 would have been construction traffic and winter maintenance operations. Therefore the 10/31/08 test results should represent changes to the surface subsequent to the 5/23/08 testing as a result of recent construction related/winter operations.

The 10/23/07 measurements reflect the friction of the surfaces just after original diamond grinding and just prior to opening to traffic. The random transverse tined section (e.g. RTT) is adjacent to the test diamond ground sections and is a 14 yr old surface.

One of the more remarkable aspects of data presented in Figure 17 is that the smooth tire results are higher than the ribbed tire results for the diamond ground surfaces. This is not the case for the random transverse tining which exhibits the difference found on most typical surfaces. At this time this finding is not well
understood by the author. However, for the NGCS section, the data is essentially identical between the 5/28 and 10/23/08 testing as would be expected. This would suggest that the repeatability of the MnDOT testing is very good. Since the NGCS has large lands (see Figure 12), it would not be expected to change much due to construction traffic or winter maintenance operations.

The NGCS smooth tire results are essentially the same after five months of traffic as when it was constructed. This would seem appropriate as the surface is essentially a “manufactured” surface at the beginning and little change is expected.

The NGCS LITE is a recently developed surface to provide an economical renewable surface for the NGCS. This surface is intended to develop more micro-texture on the land area. It is a further development of the NGCS concept. The texture produced by the NGCS LITE can be produced in the original NGCS construction or it could be used to “touch-up” the texture on the land if it ever became necessary. The “touch-up” process could be accomplished very cost effectively since little material is being removed. It’s intended to re-establish or improve micro-texture.

**EFFECTS OF LONGITUDINAL GROOVING ON FRICTION LEVEL**

In evaluating the NGCS surfaces it kindled new interest in the benefit of longitudinal grooving. Figure 18 indicates the benefit of the grooving on an astroturf texture. Although there is only marginal difference for the ribbed tire, there is a significant difference for the smooth tire. This tends to support the California research cited previously in this paper.

![Figure 17. Friction (SN40) as a Function of Surface Texture and Time](image-url)
The development of the NGCS and NGCS LITE textures has led to the construction of seven field test sections, all of which are performing as intended. Although the journey is only just beginning for these new textures, they promise a more consistent and slightly lower noise level surface than other textures. In particular, they offer the opportunity for a renewable surface texture which may prove beneficial for future preservation activities.

REFERENCES


