Efficiency and Performance of Diamond Grinding In Texas

Prasad Buddhavarapu, Andre de Fortier Smit, and Jorge Prozzi

Department of Civil, Architectural and Environmental Engineering
The University of Texas at Austin

ABSTRACT

The paper presents the results of a study to quantify the deterioration of a diamond ground continuously reinforced concrete pavement (CRCP) surface in terms of macro-texture, skid resistance, ride quality and pavement noise over time. The influence of site specific features such as traffic speed and load, pre-texturing prior to the grinding operation, lane, wheel path, and trafficking direction on the deterioration of the surface properties is investigated. The four surface properties were measured immediately after the grinding operation and at three subsequent time intervals after 4, 9, and 15 months. Panel data analysis incorporating fixed effects is implemented to evaluate the influence of the site specific features on the deterioration of the surface properties. A significant reduction in macro-texture and skid resistance was apparent. An increase in noise was evident soon after grinding. No significant change in roughness was found. The changes in the surface properties appear to be related to traffic over time but do not appear to be influenced by the pre-existing texturing prior to grinding. Additional monitoring of the sections is recommended to better characterize the long-term benefits of diamond grinding as a rehabilitation strategy for CRCP.

1. INTRODUCTION

Continuously-reinforced concrete pavement (CRCP) is a portland cement concrete pavement type containing continuous longitudinal steel reinforcement with no intermediate joints. CRC pavements are considered synonymous with long life as they are typically designed for life spans exceeding 40 years. Of the state highway agencies that use CRCP, a majority have reported reported CRCP service lives exceeding 25 years, in a few cases, beyond 50 years (1, 2). CRCP offers adequate structural strength throughout the service life because of the ability of concrete to gain strength with time (3). Ride quality of these pavements is also reported to be fairly constant throughout the pavement design life (4), which is attributable to the absence of joint-related distresses. The long-lasting characteristics of CRCP turn it into a cost-effective alternative particularly for high-volume traffic facilities, which typically demand frequent maintenance. The Texas Department of Transportation (TxDOT) has invested considerably in CRCP to cater to the needs of high-trafficked routes; Texas has been the leading State in terms of CRCP lane mileage (2) across the USA.

Besides the structural strength that accommodates traffic loading, pavement is expected to offer acceptable skid resistance to ensure a safer ride particularly under wet surface conditions. Pavement surface texture continuously wears away due to traffic, which is reflected in the form of reduced skid resistance. The rate of deterioration depends on the aggregate type used in the concrete during pavement construction, limestone being the inferior performer. Additionally, road user serviceability and road borderer concerns such as pavement noise are becoming predominant issues especially on CRCP located in urban neighborhoods. Routine maintenance of continuously deteriorating, but structurally sound, CRCP may improve its functionality in providing adequate friction and minimizing noise levels. TxDOT has been using thin asphalt overlays such as Permeable Friction Course (PFC) for improving the functionality of CRCP (5). Diamond grinding is one of the relatively inexpensive maintenance techniques for CRCP, albeit uncommon in Texas. Diamond grinding is an effective and economical alternative to maintain concrete pavements in good structural condition. (6).

The TxDOT Fort Worth district has experimented with the feasibility of adopting diamond grinding as a regular maintenance technique, particularly for functional improvements (such as skid resistance, noise etc.). A recent study on a 20- to 40-year-old 8.7-mile long CRCP section on IH 35W (5) evaluated the immediate benefits of this diamond grinding operation in improving the functionality of the CRCP; the benefits were quantified in terms of macro-texture, skid resistance, ride quality, and noise reduction. A statistically significant improvement in the following functional properties was reported: 1) surface texture (MPD) improved by 0.7 millimeters, 2) skid resistance increased by 60%, 3) overall ride quality decreased by 44 inches/mile, and 4) a noise reduction of 3.2 dBA was observed. Despite such appreciable immediate functional improvements, the durability of the reported benefits remains unclear. It is important to quantify the deterioration tendencies of the diamond ground surface in terms of the relevant functional properties. Buddhavarapu et al. (5) mentioned that the cost of resurfacing with diamond grinding is approximately less than half the estimated cost of an asphalt overlay, based on TxDOT's experience. TxDOT reportedly saved approximately $3 million by using diamond grinding instead of constructing an asphalt overlay; Rao et al. (6) also mentioned that grinding costs are substantially lower than an overlay. Long-term monitoring of the diamond ground surface would provide evidence for justifying the associated savings. It also assists TxDOT (and possibly other agencies) in evaluating the strategy of adopting diamond grinding as a maintenance technique for regular restoration of the functional properties of deteriorating and aged CRCP in Texas.

This paper aims to quantify the medium-term functional performance of the diamond ground section on IH 35W. Researchers monitored the diamond ground CRCP surface for a period of 15 months after the grinding operation; essential functional properties (macro-texture, skid resistance, surface smoothness and pavement noise) were measured four times during this period. Panel-data models were developed to quantify and statistically test the significance of the deterioration of relevant functional improvements. The paper provides a brief review of the long-term performance of diamond ground pavement surfaces. Details on the experimental design and data collection are then discussed following which the model building, estimation and selection methods are described. A comprehensive discussion on the modeling results is then provided and the paper concludes by highlighting the major findings and identifying limitations and potential for future research.

1.1 BACKGROUND

Tex Diamond grinding is a concrete pavement restoration (CPR) technique that improves friction characteristics while providing a smoother ride on concrete pavements (6). Typically, diamond grinding involves removing a thin layer off the top of the pavement using a stack of circular blades separated at regular and relatively small intervals and thereby leaving a longitudinal textured surface with very thin projections or fins between the saw-cut grooves. In 1956, diamond grinding was first used to correct localized profile problems on a new concrete taxiway at Davis Monthan Air Base in Tuscon, Arizona (6). However, diamond grinding was first used as a CPR technique later in 1965. A 19-year-old jointed concrete pavement section on San Bernardino Freeway in California was diamond ground to eliminate excessive faulting (7). Subsequently, the same pavement section was successfully reground two more times (in 1983 and 1997) as part of the routine pavement restoration program (6). The success of this initial project led to implementation of diamond grinding as a major element of CPR throughout the US and the world.

In 1999, the Portland Cement Association (PCA) in association with American Concrete Pavement Association (ACPA) and International Grooving and Grinding Association (IGGA) sponsored a study to evaluate both short-term and long-term performance of the diamond ground projects. The study (6) used a database consisting of 120 diamond ground sections obtained from a FHWA study (8). Additionally, more such sections from SPS-6 (Special Pavement Studies) experiment of Long Term Pavement Performance (LTPP) were added to the database. A side-by-side comparison of diamond-ground pavement sections and other alternatives, such as asphalt concrete overlay, was performed using LTPP data (6). Rao et al. (6) also estimated the longevity of the diamond ground sections. This review includes the most important and relevant findings of this study focusing on the long-term performance of diamond ground pavement in terms of ride quality and surface texture. A significant short-term improvement in ride quality was evident in numerous diamond grinding projects across the U.S. (5, 6). Rao et al. (6) mentioned that the improvement in terms of ride quality that is achievable by diamond grinding operation is on par with that of a new overlay; they reported that no significant difference in International Roughness Index (IRI) between diamond grinding and asphalt overlaid sections was evident even after four years of service life. The long-term deterioration characteristics of ride quality of diamond-ground pavements depends on numerous factors such as pavement design and condition, the level of patching and repair work prior to diamond grinding, the traffic level, and climatic conditions. Richter (4) reported that the roughness of CRCP remains fairly constant at the initial roughness level for a very long duration (4); therefore, the ride quality deterioration may not be a primary issue in CRCP.

The longitudinal texture of the diamond grinding causes an immediate increase in the macro-texture of the pavement surface, thereby improving skid resistance of the surface. The longitudinal grooves also improve the drainage of rain water and further reduce the chance of hydroplaning during wet conditions. Pavements containing aggregates that are susceptible to polishing are possibly associated with only temporary improvement in skid numbers and wear away with time (9). However, interestingly, Rao et al. (10) reported that aggregate hardness has no effect on the longevity of diamond-ground surface texture; the effects of aggregate hardness may be nullified because of the closer blade spacing typically used on harder aggregates; it results in smaller land area that would wear down as fast as softer aggregate counterparts. They observed that although the skid numbers will decrease over the first few years, an adequate macro-texture normally will be maintained for many years. Rao et al. (10) showed that the longevity of diamond-ground texture is strongly correlated to the age since grinding and climatic region (the texture lasting longer in non-freeze climates). A drop of 0.76 mm was reported within the first 2 to 2.5 years, and the rate of change of macro-texture appears to decreases with time; texture was reported to last from 8 to 12 years, depending on freezing conditions. The diamond ground surface offers micro-texture after fin breakage, which may improve both dry and wet skid resistance. The longevity of the skid resistance is arguably similar to that of the surface texture.

In the literature, concrete pavement surfaces with longitudinal texture are reported as the quietest (11), which further emphasizes the noise reduction capabilities of the diamond grinding operation. A considerable number of earlier studies reported the evidence of significant noise reduction immediately following diamond grinding (6, 12, 13); they further emphasized that grinding alters the frequency of pavement noise, reducing the objectionable “tonal” content (13). In general, noise is believed to be related to surface macro-texture, particularly for dense graded asphalt mixtures (14). A pavement surface with higher macro-texture reduces the noise level at high frequencies, while the pavement with lower macro-texture is quieter at low frequencies (15). The long-term performance of the diamond ground surface in terms of pavement noise has seldom been reported in the literature. Perhaps, noise reduction capabilities deteriorate in the same order as the rate of deterioration of the surface texture.

Rao et al. (6) quantified the effectiveness of diamond grinding in extending service life based on a survival analysis using 76 individual diamond ground pavement projects. The probability of a structurally sound diamond ground pavement carrying more than 5 million axles was estimated as 95% and to last at least 10 years was 88%. Rao et al. (6) also reported an average life extension of 12.9 years since the first grind for diamond ground sections. The literature review highlights the long-term performance of diamond grounding in maintaining the functional aspects of concrete pavements. It is important to note that the majority of the earlier studies evaluated Jointed Concrete Pavements (JCP); this study adds to the existing literature by documenting the functional deterioration characteristics (macro-texture, skid resistance, ride quality and pavement noise) of a diamond ground CRCP.

1.2 STUDY OBJECTIVES

The primary objective of the study is to assess the endurance of diamond-ground surfaces in offering a skid resistant, smoother, and quieter ride towards evaluating the suitability of diamond grinding for concrete pavement maintenance. The study quantifies the changes in the following four functional characteristics with time: macro-texture, skid resistance, ride quality, and pavement noise. The study also quantifies the influence of site specific features, such as the pre-existing surface condition or pre-texturing (e.g., carpet-drag, burlap-drag and transverse tinning) and traffic on the relatively short-term performance of diamond grinding. The researchers designed an experimental program to facilitate comprehensive data collection of site specific features and major functional properties of interest. A panel data analysis was implemented to evaluate the influence of the pre-existing conditions and site specific features on the deterioration of the relevant functional properties.

2. DATA

This section introduces the site of the Fort Worth diamond grinding project on a CRCP section of IH 35W, while the later part describes the comprehensive experimental program in more detail.

An 8.7-mile stretch of the freeway facility, originally constructed as a CRCP, was uniformly diamond-ground; the site layout is shown in Figure 1. The pavement segment was divided into three different sections based on the type of pre-existing condition prior to the grinding as follows:

1. Section 1: Pre-textured using carpet drag,
2. Section 2: Pre-textured using burlap drag, and,
3. Section 3: pre-textured using transverse tinning.

These sections are not of uniform length, Section 1 being the longest and Section 3 being the shortest.

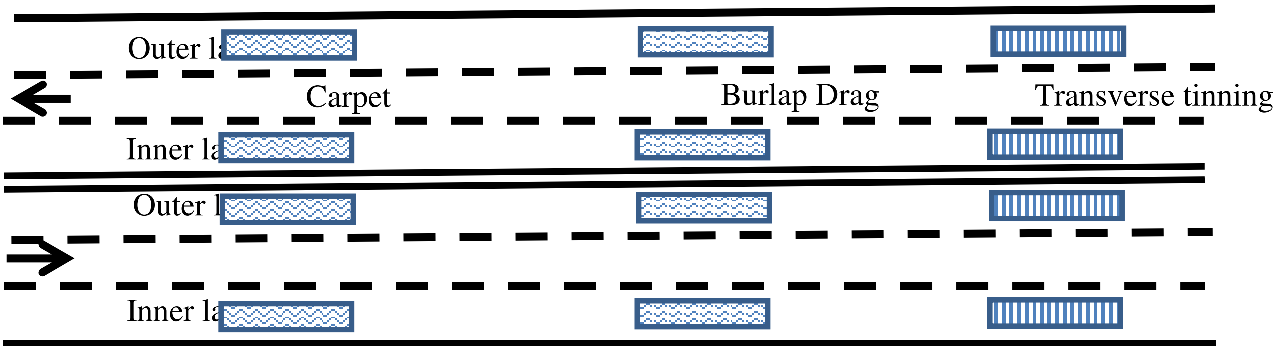

FIGURE 1 Site of the diamond ground test sections in Fort Worth

An experimental program was devised to measure the functional properties of the diamond ground CRCP at four different time intervals over a period of 15 months; measurements were collected immediately after the grinding operation and subsequently after 4 months, 9 months and 15 months. Macro-texture, skid resistance, ride quality and pavement noise were measured as part of this field-testing program. In an effort towards quantifying the influence of site-specific features and traffic, measurements were taken at 12 different locations across the 8.7-mile pavement segment as shown in Figure 1 (hatched blocks represent experimental locations). A detailed description of the test methodologies adopted for obtaining information on the various functional properties is provided below.

2.1 SURFACE MACROTEXTURE

Macro-texture was measured using the Circular Texture Meter (CTM), which is a laser based device for measuring surface texture of pavements per ASTM E2157. The CTM has a charged couple device laser displacement sensor which is mounted at a height of 80 mm from the surface on a rotating arm. The arm rotates at a tangential velocity of 6mm/min in a circular motion with a radius of 142 mm. The CTM uses a laser to measure the profile along the circumference of a circle. To calculate the mean profile depth (MPD), the data along the circle is divided into eight equal arcs each 111.5 mm in length. The calculated MPD for each segment is averaged and presented as the MPD for the test surface. Nine measurements spanning across the lane in the left and right wheel paths and between the wheel paths were obtained at each of the 12 test locations mentioned in Figure 1. A total of 108 measurements were obtained at four time intervals (0, 4, 9, 15 months) during the analysis period.

2.2 SKID RESISTANCE

Skid resistance was measured by TxDOT's skid trailer per ASTM E524 using a smooth tire (ASTM E1844) at a speed of 50 mph under wet conditions. The skid trailer provides a skid number, which is the ratio of lateral friction and the normal reaction multiplied by 100. While skid numbers range from 1 to 100, values above 70 are rare. Skid measurements were collected almost continuously with a frequency of one per 0.1 mile along the 8.7 mile long CRCP section. Skid data was collected separately on the outer and inner lanes as well as in the north- and south-bound directions at each time interval (0, 4, 9, 15 months) throughout the analysis period. Skid data was only collected in the right wheel path of the measured lane.

2.3 RIDE QUALITY

Ride quality was measured using a high-speed inertial profiler vehicle at highway speeds. The inertial profiler is equipped with two-point lasers on both wheel paths. It collects pavement elevation at an interval of approximately 2 inches at high speeds (around 50 mph); the elevation information is then combined with an accelerometer to eliminate the vehicle dynamics. Ride quality is typically reported every 0.1 mile. Roughness data were also collected separately on the outer and inner lanes as well as the north and south bound directions at each time interval (0, 4, 9, 15 months) throughout the analysis period. The roughness data were typically collected on both the left and right wheel paths of the measured lane.

2.4 PAVEMENT NOISE

Pavement noise was measured using the on-board sound intensity (OBSI) method, a commonly used technique for the measurement of tire-pavement noise; the OBSI test procedure followed complies with the AASHTO TP 76-11 specification. Noise from other sources such as the engine, exhaust, and aerodynamic effects, as well as from reflections and noise from adjacent vehicles is isolated from tire-pavement noise under the OBSI framework. The OBSI device consists of two microphones recording the noise sourced from leading and trailing locations of the tire-pavement contact patch. The proximity of the microphones to both the tire (4 in.) and the pavement (3 in.) makes this method ideal for measuring only the noise generated at the tire-pavement interface.

Tire-pavement noise was recorded at three sub-locations within each of the twelve experimental sections that are shown in Figure 1; the measurements are taken at each time interval during the analysis period. Noise was recorded at 60 mph (96 km/h) for a time period of 5 seconds. The study team collected three replicate noise measurements on each of these 36 sub-locations resulting in a total of 108 measurements at each of the time intervals (0, 4, 9, and 15 months) over the analysis period. Noise measurements were only recorded on fairly flat and straight pavements to reduce noise associated with acceleration or deceleration as well as turning, not on bridges, and away from entrance and exit ramps that can prevent the test vehicle from maintaining the test speed.

3. DATA ANALYSIS AND DISCUSSION

In this section, a summary of measured surface characteristics is presented emphasizing the overall deterioration of the diamond ground CRCP surface in terms of macro-texture, skid resistance, ride quality, and pavement noise. The later part of the section presents a methodology to further analyze the field-collected data in order to identify the influence of the site specific features such as traffic and type of existing surface texture prior to diamond grinding on the deterioration of the relevant functional properties of the diamond ground surface.

3.1 OVERALL DETERIORATION OF DIAMOND GRINDING

A preliminary glimpse of deterioration of the diamond ground surface is presented using a simple histogram of the averaged measurements of relevant surface properties. Figure 2 shows the histogram of overall averaged macro-texture (Figure 2a), skid resistance (Figure 2b), ride quality (Figure 2c), and pavement noise (Figure 2d) measured immediately after the grinding operation (indicated as 0 months) followed by three subsequent measurements at the end of 4, 9, and 15 months.

Although the figures above depict deterioration of the surface properties, a statistical approach is required to ascertain significance. Therefore, the averaged measurement at any time interval is statistically compared to its predecessor; this is to ensure that the drop or increase in the corresponding surface property is different from inherent measurement errors. The comparisons were carried out using simple linear regressions with indicator-type explanatory variables corresponding to each of the time intervals. Table 1 summarizes the results from the statistical comparison analysis including the measurements immediately after the diamond grinding operation and the subsequent changes over time; statistically significant changes are only reported along with their standard errors (in brackets).

A brief discussion on the overall deterioration characteristics of the diamond ground surface in terms of aforesaid four surface properties follows.

Surface Texture

The CTM measured macro-texture of the diamond ground surface immediately after the grinding operation was 1.3 millimeters, which is larger than the minimum required texture depth, i.e., 1.2 mm (for limestone aggregates) as per the relevant grinding specification (5). A statistically significant drop of 0.2 mm in macro-texture was evident after four months beyond which, it remained fairly constant up until 9 months. The ground surface texture further eroded by 0.1 mm during the last 6 months span of the analysis period; it is reasonable to ignore the minor, albeit statistically significant, drop of 0.1 mm in macro-texture. The initial drop within the first few months may be attributed to breakage of fins causing a decrease in macro-texture, while an increase in micro-texture is possible. The overall drop in macro-texture was estimated as 0.3 mm during the analysis period of 15 months reaching a terminal value of 1.0 mm.

Skid Resistance

The newly ground CRCP provided a skid number that is larger than 33, which is deemed adequate for ensuring a safer ride under wet conditions. The surface barely eroded within the first four months showing a statistically significant increase of 0.8, while the skid number dropped by 3 (statistically significant) in the subsequent five month period. The surface further eroded during the last six months of the analysis period, with an additional loss of 4.6 in skid value. The minor initial increase of skid resistance may be attributed to an increase in micro-texture caused due to the breakage of fins. An overall loss in skid resistance was estimated as 6.7 during the first 15 months reaching a terminal value of 27. Perhaps, the considerable deterioration in terms of skid resistance is attributable to the aggregate quality of the concrete pavement. Further measurements over time are required, however, to validate this.

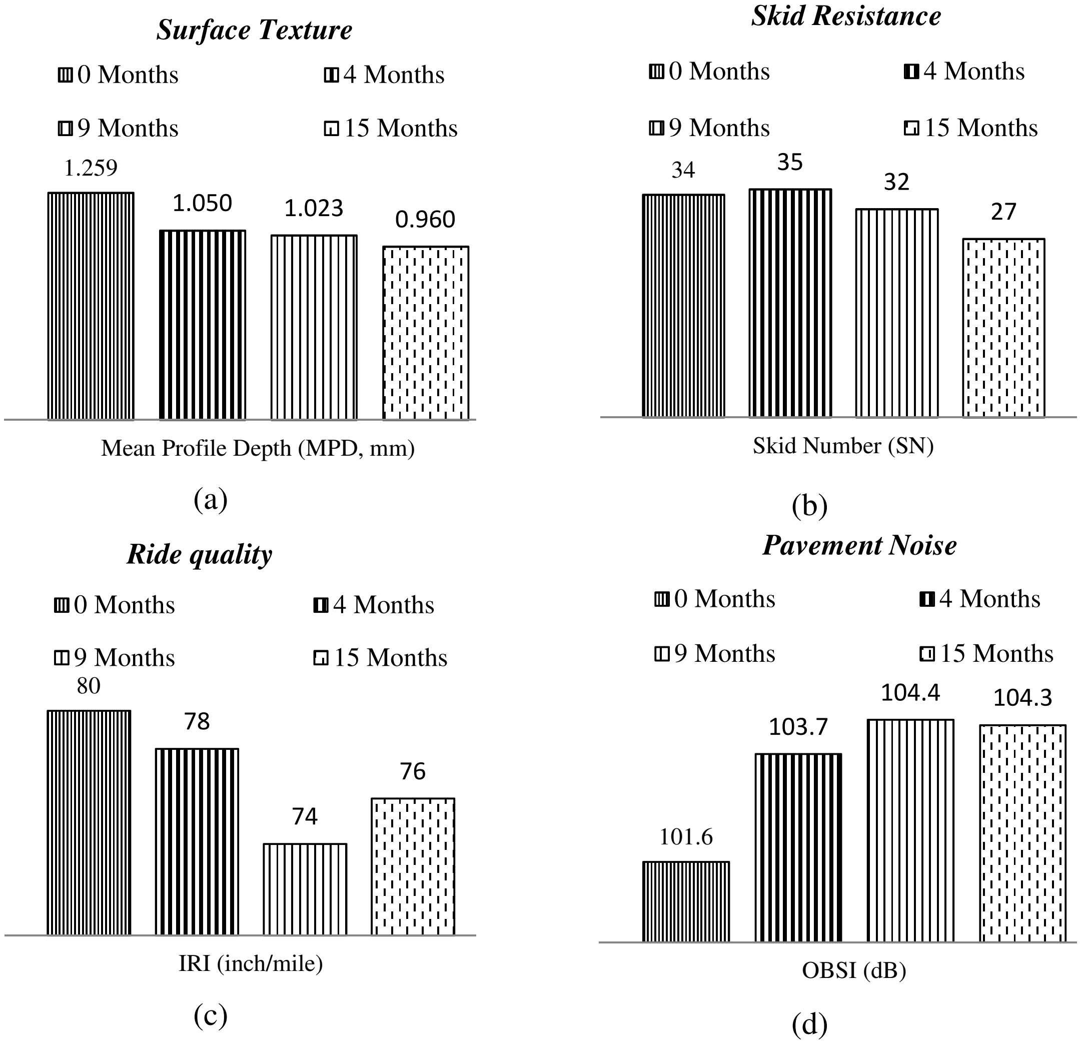

FIGURE 2 Deterioration of Surface Properties with Time

TABLE 1 Overall changes in surface properties over time

Variable Description	Surface Texture (MPD in millimeters)	Skid resistance (Skid Number)	Ride quality (IRI in inch/mile)	Pavement Noise (OBSI in dBA)
Measurement immediately after diamond grinding	1.26 (0.02)	34.0 (0.19)	79.9 (0.8)	101.6 (0.15)
Change at: Measurement after 4 months	-0.21 (0.03)	0.8 (0.27)	-	2.1 (0.17)
Change at: Measurement after 9 months	-	-3.0 (0.27)	-4.2 (1.1)	0.7 (0.12)
Change at: Measurement after 15 months	-0.06 (0.03)	-4.6 (0.26)	-	-
Overall change during the analysis period	-0.30 (0.03)	-6.7 (0.26)	-3.9 (1.1)	2.7 (0.17)

Note: The standard error is provided within brackets.

Ride quality

Although roughness is not a major issue in CRCP, diamond grinding reduces the roughness possibly generated by any prior local patches and repairs. The overall averaged roughness level of the newly ground CRCP is estimated at 80 inch/mile as shown in Figure 2 at the beginning of the analysis period. The roughness was maintained at a fairly constant level for the first few months and dropped significantly by 4.2 inch/mile at the end of 9 months; subsequently, the roughness stabilized and has not shown any significant changes. A terminal value of 76 inch/mile was reported at the end of the analysis period of 15 months. The initial drop of 4.2 inch/mile is slight, albeit statistically significant, and it can be concluded that the roughness remained reasonably constant throughout the analysis period. In this aspect, diamond grinding was successful in retaining the post-ground surface smoothness during the first 15 months following construction. Indeed, the finding is expected considering the structural strength and absence of joint-related distresses in CRC pavements.

Pavement Noise

Diamond grinding significantly reduced the tire-pavement noise with an overall reduction of more than 3 dBA (5). An average noise intensity of 101.6 dBA was reported on the newly ground CRCP immediately after the grinding operation. As shown in Figure 2 the tire-pavement noise intensity considerably increased within the first few months. A significant increase of 2.1 dBA was evident within the first 4 months, followed by a further increment of 0.7 dBA at the end of 9 months. An overall statistically significant noise level increase of 2.7 dBA was reported within a period of 15 months. Compared with the immediate noise abatement of 3.2 dBA, (5) the increase in noise levels appears to nullify the initial benefit of utilizing diamond grinding as a noise abatement technique.

3.2 INFLUENCE OF SITE FEATURES ON DETERIORATION OF DIAMOND GRINDING

The influence of traffic speed and load, pre-existing texture prior to the grinding and other site specific variables was investigated. Individual regression models were estimated for understanding the influence of site features on deterioration of diamond grinding in terms of macro-texture, skid resistance, ride quality and pavement noise. A panel-based regression approach was implemented that recognizes the panel setting of the field-data collected at different time intervals. A detailed methodology utilized for model development and estimation along with the modeling results is provided below.

Model Development

The field-collected data includes measurements of four different surface properties along with the site specific features associated with each measurement location. The measured surface properties are modeled as continuous dependent variables while incorporating the site specific features, represented as categorical explanatory variables. To achieve the main objectives of this paper, the field data was collected at multiple times during the analysis period of 15 months. A linear regression of the pooled data (collected at multiple time intervals) would yield biased estimates in such scenarios; ignoring the time dependent effects would generate omitted variable bias. The influence of the site specific features may only be extracted accurately by accounting for the inherent time dependent effect on the measured surface properties, which is a typical panel data problem. Panel data is commonly handled using either fixed or random effects approaches. The former approach assumes the time dependent effect is correlated with the other explanatory variables in the model, while the later assumes no correlation. Intuitively, the increase or decrease of the surface properties (texture, skid resistance, ride quality, or pavement noise) between any two time intervals is possibly related to the features of the measurement location. For instance, the loss of skid resistance is arguably related to the traffic speed and load, which may be deduced from data collected in the corresponding lane i.e., the outer lane carries slower and heavier traffic, while the inner lane carries faster and lighter traffic. In order to account for such potential correlations, a panel regression model using fixed effects was adopted. One way of estimating the fixed effects model is by introducing indicator variables representing each panel or time interval in this case. Additionally, these time-related indicator variables are interacted with explanatory variables to estimate the variation of the influence of site specific features on measured surface properties. Subsequently, estimation of a linear regression model including the time related indicator variables, explanatory variables of interest, and the interactions would yield unbiased estimates, even though the estimates are obtained using simple ordinary least squares estimation procedures. The regression model that is being estimated in this study is presented below.

$$\mathrm{Y_{it}} = \beta_0 + \mathrm{T}\alpha + \mathrm{X_i}\beta + \{\mathrm{X_i} * \mathrm{T}\}\gamma + \epsilon_{\mathrm{it}} \quad (1)$$

where,

$\mathrm{Y_{it}}$: $\mathrm{i^{th}}$ observation of the surface property measured at $\mathrm{t^{th}}$ time spot.

β_0: Constant that absorbs information relevant to the base case

T: Vector of indicator variables corresponding to 4, 9 and 15 month time intervals; the base level is selected as measurement immediately after the grinding (0 months).

α: Vector of fixed effects corresponding to 4, 9 and 15 month time periods

$\mathrm{X_i}$: Vector of explanatory variables corresponding to $\mathrm{i^{th}}$observation at $\mathrm{t^{th}}$ time interval. It is important to note that the explanatory variables or site features do not change over time

β: Vector of overall regression coefficients corresponding to the explanatory variables

γ: Vector of regression coefficients corresponding to the interaction of explanatory variables and time-related indicator variable; these are also another form of fixed effects.

ϵ_{it}: Idiosyncratic error term

The model coefficients and the corresponding standard errors are obtained through ordinary least squares estimation of the model presented in Equation 1. A final specification was chosen carefully based on a rigorous model development process including all the aforementioned variables. Model refinement was carried out using standard statistical tests (such as the F-test) and exclusion of statistically insignificant variables. Practical considerations played a role in the removal of insignificant variables, rather than solely adopting a statistically based mechanical approach. Table 2 presents the final specification estimates corresponding to each of the surface properties measured as part of the study.

3.3 MODEL RESULTS AND DISCUSSION

A brief discussion on both magnitude and sign of the estimated coefficients corresponding to the final specification is provided below; four specifications corresponding to surface texture, skid resistance, ride quality, and pavement noise are discussed. The discussion primarily revolves around the influence of the following site specific features on the deterioration of diamond grinding: (a) pre-texturing (carpet drag, burlap drag and transverse tinning), (b) traffic type, (c) direction of the traffic, and (d) wheel path location.

Surface Texture:

With reference to Table 2, the negative sign on the coefficients corresponding to the carpet-drag and burlap-drag surfaces reflects that the surface texture on the transversely tined section is higher immediately after the diamond grinding; intuitively, the transverse tining is expected to possess deeper texture, which is in agreement with the coefficient signs. The coefficients corresponding to interaction of the carpet and burlap drag indicator variables with the time-related indicators were not statistically significant (hence, not reported in Table 2); therefore, it is concluded that the pre-texturing type existing prior to the grinding does not influence the deterioration of the surface texture over time.

Second, the positive sign on the coefficient corresponding to the slower and heavier traffic indicator variable indicates that lanes carrying slower heavier traffic have a higher surface texture than that of lanes carrying faster lighter traffic immediately after the grinding; this is attributed to construction related variations. However, it is interesting to observe that the lanes carrying slower heavier traffic deteriorated more rapidly than the lanes carrying the faster lighter traffic; this being reflected by the negative signs on the coefficients corresponding to the time and traffic interaction variables. The magnitudes of the coefficients corresponding to these interactions indicate a moderate texture deterioration of the outer lane within the first few months followed by the faster deterioration in the last six months of the analysis period. It is concluded that traffic characteristics such as traffic speed and load influences the deterioration of the surface texture of diamond ground surfaces.

Third, the positive sign on the south bound indicator reflects a higher surface texture in the south bound direction immediately following grinding. The south bound lanes continuously eroded loosing further texture within the first four months and remained on par with that of north-bound direction thereafter.

Finally, the negative sign on the left wheel path indicator reflects that the left wheel path had the lowest surface texture immediately after the diamond grinding. The negative signs on the relevant interaction indicator variables indicate that the texture on the right wheel path eroded faster than that on left wheel path.

Skid Resistance:

The negative sign of the coefficient corresponding to the burlap drag indicator variable represents a lower skid resistance, though a relatively smaller difference, on locations that are pre-textured with burlap drag relative to that with transverse tining immediately after the grinding operation; there was no statistically significant difference in terms of skid between the surface pre-textured with carpet drag and that with transverse tining. The coefficients corresponding to interaction of the carpet and burlap drag indicator variables with the time-related indicators were not statistically significant; therefore it is concluded that the pre-texturing type existing prior to the grinding did not influence the deterioration of the skid resistance over time.

For the slower heavier traffic indicator, the negative sign on the corresponding coefficient reflects a relatively lower skid resistance on the lanes carrying slower heavier traffic in comparison with that on lanes carrying faster lighter traffic, which is intuitive. The statistical insignificance of coefficients of the time and traffic interaction variables indicates that traffic speed and load did not influence the deterioration of the skid resistance within the first nine months. However, the lanes carrying slower heavier traffic deteriorated considerably faster than lanes carrying faster lighter traffic loosing considerable skid resistance during the last six months of the analysis period. It is therefore concluded that traffic speed and load do influence the deterioration of the skid resistance of diamond ground surfaces, particularly after the first few months.

TABLE 2 Influence of site features on deterioration of ground CRC surface

Variable category	Explanatory Variable Description	Surface Texture (MPD in millimeters)	Skid resistance (Skid Number)	Ride quality (IRI in inch/mile)	Pavement Noise (OBSI in dBA)
Indicator variable	Constant	1.293 (0.028)	33.61(0.28)	76.45 (1.17)	102.18 (0.14)
	Time2 (Measurement at 4 months)	-0.129 (0.039)	1.54 (0.37)	-3.79 (1.25)	1.97 (0.16)
	Time3 (Measurement at 9 months)	-0.111 (0.034)	-1.29 (0.36)	-8.82 (1.34)	2.80 (0.14)
	Time4 (Measurement at 15 months)	-0.182 (0.034)	-5.29 (0.41)	-5.64 (1.35)	2.38 (0.16)
	Pre-existing surface condition (Transverse tining is base level):				
	Carpet drag	-0.077 (0.020)	-	5.26 (1.08)	-0.86 (0.10)
	Burlap Drag	-0.092 (0.020)	-0.71 (0.19)	2.19 (1.14)	-0.95 (0.10)
	traffic type (faster lighter traffic is base level):				
	Slower, heavier traffic	0.110 (0.032)	-0.78 (0.21)	-	-
	Direction of traffic (North-bound is base level):				
	South-bound	0.067 (0.019)	1.93 (0.36)	-	-
	Wheel Path location (between wheel paths is base level):				
	Left wheel path	-0.199 (0.019)	- NA-	- NA-	-NA-
	Right wheel path	-	- NA-	-	-NA-
Interaction between indicator variable	Time2 & south-bound	0.085 (0.037)	-1.47 (0.51)	-	-
	Time3 & south-bound	-	-1.79 (0.51)	-	-
	Time4 & south-bound	-	-1.09 (0.51)	-	-
	Time2 & Slower, heavier traffic	-0.131 (0.046)	-	-	0.30 (0.14)
	Time3 & Slower, heavier traffic	-0.136 (0.046)	-	-	-
	Time4 & Slower, heavier traffic	-0.144 (0.046)	-1.83 (0.41)	-	0.64 (0.14)
	Time2 & left wheel path	-	- NA-	- NA-	-NA-
	Time3 & left wheel path	-	- NA-	- NA-	- NA-
	Time4 & left wheel path	-	NA-	- NA-	- NA-
	Time2 & right wheel path	-0.169 (0.036)	- NA-	4.26 (1.39)	- NA-
	Time3 & right wheel path	-0.172 (0.036)	- NA-	5.96 (1.55)	- NA-
	Time4 & right wheel path	-0.134 (0.036)	- NA-	4.35 (1.56)	- NA-

Note: 1. The standard error is provided within brackets.
2. –NA– represents unavailability of the measurement
3. – represents statistical insignificance of the coefficient

The positive sign on the coefficient corresponding to the south-bound indicator variable reflects larger skid resistance on experimental sections in the south-bound traffic direction than that of sections in the north-bound direction. However, the negative sign on the relevant interaction variables indicates that the experimental sections located in the north-bound direction lost skid resistance more rapidly than that in south-bound direction during the analysis period.

Ride quality: The positive sign of the coefficients corresponding to the carpet-drag and burlap-drag indicator variables indicate that the experimental sections pre-textured with transverse tining were smoother than that with carpet or burlap drag, immediately after grinding. The coefficients corresponding to interaction of the carpet and burlap drag indicator variables with the time-related indicators were not statistically significant; therefore it is concluded that the pre-texturing type existing prior to grinding did not influence the deterioration of the surface smoothness with time. Also, the statistical insignificance of the traffic related indicator variables highlights that the traffic speed and load did not influence the deterioration of the ride quality. Intuitively, this finding is reasonable considering the underlying structurally sound CRCP. It is also observed that traffic direction does not influence the deterioration rate of the ride quality. Finally, the statistical insignificance of the coefficient of the right wheel path indicator variable indicates that there was no difference in the ride quality of the left and right wheel paths immediately after grinding. However, the right wheel path deteriorated faster than the left wheel path within the analysis period; this is indicated by the positive coefficient of the relevant time-related interaction variables. The greater deterioration rate of texture in the right wheel path is possibly the result of cross-slope and the slightly greater vehicle weight being placed in this wheel path.

Pavement Noise: The negative coefficient of the indicator variables corresponding to the carpet-drag and burlap-drag indicate that the transversely tined pavement was the loudest immediately after the grinding operation. The coefficient corresponding to the interaction of the carpet and burlap drag indicator variables with the time-related indicators were not statistically significant; therefore it is concluded that the pre-texturing type existing prior to the grinding did not influence the deterioration of the pavement noise reduction ability with time. Additionally, the statistical insignificance of the traffic related indicator variable indicates that the noise levels on both the inner and outer lanes were similar immediately after grinding. However, within the first four months, the lane carrying slower and heavier traffic became louder and by the end of the analysis period, the noise levels on the outer lane increased further. Hence it appears that both traffic speed and load contribute to the increased noise levels, albeit indirectly. Finally, no significant difference in noise level was evident between the north- and south-bound lanes.

4 CONCLUSIONS

The primary objective of the study on which this paper is based is to quantify the medium-term performance of a diamond-ground CRCP surface in retaining essential surface properties. The influence of site specific features such as traffic speed and load, the pre-existing surface condition or pre-texturing (such as carpet-drag, burlap-drag and transverse tining), wheel path, and trafficking direction on the deterioration of the diamond grinding is also quantified. Macro-texture, skid resistance, ride quality, and pavement noise were monitored for a period of 15 months using the CTM, TxDOT skid trailer, inertial profiler, and OBSI noise measuring equipment respectively. The surface properties were measured immediately after the grinding operation and at three subsequent time intervals, i.e., after 4, 9, and 15 months. An experimental program was developed to facilitate comprehensive data collection covering the site specific features addressing the primary surface properties of interest. The overall deterioration characteristics of the measured surface properties are discussed using sound statistical techniques. A panel-type regression approach incorporating fixed effects is implemented to evaluate the influence of the site specific features on the deterioration of the relevant surface properties.

The deterioration of the diamond grinding is observed to be different for each of the four measured surface properties. First, MPD dropped by 0.2 mm after 4 months beyond which it remained fairly constant up until 9 months; it showed further indications of wear, though minimal loss in texture is apparent during the last 6 months of the analysis period. The overall drop in macro-texture was estimated as 0.3 mm during the analysis period of 15 months reaching a terminal value of 1 mm.

Second, the surface barely eroded within the first four months in terms of skid resistance, subsequently, the skid number dropped by 3 during the following five month period. The surface further lost an additional 4.6 in skid number during the last six months of the analysis period. The data suggests an overall loss of 6.7 in skid number during the first 15 months, reaching a terminal value of 27. The loss in skid resistance may be attributed to the aggregate (limestone) type quality of the concrete pavement.

Third, the roughness maintained fairly constant for the first few months and dropped significantly by 4.2 inch/mile at the end of 9 months; subsequently, the roughness stabilized and has not shown any significant changes. A terminal value of 76 inch/mile is reported at the end of the analysis period of 15 months. It is concluded that the roughness is reasonably constant throughout the analysis period thus diamond grinding was beneficial in providing a smoother pavement during the first 15 months in service.

Fourth, tire-pavement noise intensity increased by 2.1 dBA within the first 4 months followed by a further increment of 0.7 dBA at the end of 9 months. An overall significant noise level increase of 2.7 dBA was reported within a period of 15 months. Despite a noticeable immediate noise reduction, (5) diamond grinding does not appear to be effective in reducing noise levels over extended periods.

In general, it was found that four site-specific features controlled the deterioration of the diamond grinding in terms of the monitored surface properties. First, based on the model estimates, pre-texturing type existing prior to the grinding operation did not appear to have influenced the deterioration of essential surface properties monitored as part of the study. Second, slower and heavier traffic accelerated the deterioration of macro-texture, skid resistance and pavement noise abatement. Third, according to observed data the direction of the trafficking appears to influence macro-texture and skid resistance, although the reason for this is unclear. Fourth, more rapid deterioration was observed in the right wheel path, in terms of macro-texture as well as ride quality.

In summary, the study provides statistical evidence that the diamond ground surface did deteriorate in terms of macro-texture, skid resistance, roughness, and noise after 15 months in service – but additional measurements and monitoring of the sections over time is recommended to better model this deterioration towards establishing the long-term benefits.

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REFERENCES

1. Hall, K., D. Dawood, S. Vanikar, R. Tally, T. Cackler, A. Correa, P. Deem, James Duit, G. Geary, A. Gisi, A. Hanna, S. Kosmatka, R. Rasmussen, S. Tayabji, and G. Voigt, “Long-Life Concrete Pavements in Europe and Canada,” Publication, FHWA-PL-07-027, FHWA, U.S. Department of Transportation, 2007.
2. The Transtec Group, Inc., “CRCP in Texas: Five Decades of Experience,” Research Series No.11, Concrete Reinforcing Steel Institute, 2004.

3. Mindess, S., and J.F. Young, Concrete, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1981.
4. Richter, C., “What Makes Portland Cement Concrete (PCC) Pavements Rough?” Publication No. FHWA-RD-98-148, FHWA, U.S. Department of Transportation, 1998.
5. Buddhavarapu, P., A de F. Smit, A. Banerjee, M. Trevino, and J. A. Prozzi, “Evaluation of the Benefits of Diamond Grinding of CRCP in Texas,” Accepted for publication in Transportation Research record: Journal of the Transportation Research Board, No.1983, Transportation Research Board of the National Academies, Washington, D.C., 2013.
6. Rao, S., H.T. Yu, and M.I. Darter, “The Longevity and Performance of Diamond-Ground Pavements,” Research and Development Bulletin RD118, Portland Cement Association, Skokie, Illinois, U.S.A., 1999.
7. Neal, B. F. and J. H. Woodstrom, “Rehabilitation of Faulted Pavements by Grinding,” Report, CA-DOT-TL-5167-4-76-18, California Department of Transportation, Sacramento, Caliornia, 1976.
8. Snyder, M. B., M. J. Reiter, K. T. Hall, and M.I. Darter, “Rehabilitation of Concrete Pavements, Volume I: Repair Rehabilitation Techniques,” Report, FHWA-RD-88-071, Federal Highway Administration, Washington, D.C., 1989,
9. Mosher, L. G., “Restoration of Final Surface to Concrete Pavement by Diamond Grinding,” Presented at Third International Conference on Concrete Pavement Design and Rehabilitation, Purdue University, West Lafayette, Indiana, 1985.
10. Rao, Shreenath, H. Yu, Lev Khazanovich, Michael Darter, and James Mack, "Longevity of Diamond-Ground Concrete Pavements,” Transportation Research Record 1684.1 (1999): 128-36.
11. Marquette University, “Noise and Texture on PCC Pavements – Results of a Multi-State Study,” ACPA Technorandum, American Concrete Pavement Association, Skokie, IL, 1998.
12. Scofield, L., “Arizona SR202 PCCP Whisper Grinding Test Sections Final Report,” Arizona Department of Transportation, Technical Information, International Grinding and Grooving Association, 2003.
13. Defrain, L., “Noise Analysis of Ground Surface on I-69 WB Near Lowell Road C.S. 19043,” Research Project 88 TI-1342, Office Memorandum, Michigan Department of Transportation, Lansing, Michigan, 1989.
14. Hanson, D.I. and Prowell, B.D., “Evaluation of Circular Texture Meter for Measuring Macro texture of Pavements,” NCAT Report 04-05, National Center for Asphalt Technology, Auburn, Alabama, 2004.
15. Dare T., W. Wulf, T. Thornton, and R. Bernhard, “Acoustical Effects of Grinding and Grooving on Portland Cement Concrete Pavements,” Technical Information, International Grinding and Grooving Association, 2009.

Author Biography

Prasad Buddhavarapu

Prasad Buddhavarapu is currently a doctoral student at The University of Texas at Austin in the Department of Civil Engineering. He received his M.S. in Civil Engineering from the University of Texas at Austin in 2011. He is also currently working on another Master's degree in Statistics along with his doctoral degree. Prasad's primary research interests are in the areas of statistical modeling of transportation data and pavement management. He is currently working on developing a network level safety index which includes modeling of historical crash count data while accounting for spatial and temporal correlation using Hierarchical Bayesian modeling techniques. He has previously worked on a few research projects including pavement material engineering, quality management in pavement construction, pavement performance data collection and diamond grinding.