Construction and Building Materials 101 (2015) 602–610

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

# Milled pavement texturing to optimize skid improvements

Lu Gao [a,*], André de Fortier Smit [b], Jorge A. Prozzi [b], Prasad Buddhavarapu [b], Mike Murphy [b], Lingguang Song [a]

[a] Department of Construction Management, University of Houston, Houston, TX 77204, USA
[b] Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, Austin, TX 78712, USA

## HIGHLIGHTS

- Pavement texturing can improve flexible pavement's skid resistance.
- A forward speed of 70–80 feet per minute is recommended.
- A cutting depth between 0.25 and 0.5 inches are recommended.

## ARTICLE INFO

*Article history:*
Received 29 April 2015
Received in revised form 2 May 2015
Accepted 15 October 2015

*Keywords:*
Pavement texturing
Milling machine
Skid resistance
Macrotexture

## ABSTRACT

This research evaluated the use of a milling machine to texture pavement surfaces and its effect on skid improvement. Texturing tests with different milling drums, forward speeds and cutting depths were conducted on 31 asphalt pavement sections across Texas. Macrotexture and friction were measured before the milling and 3, 6, 12, and 18 months after the milling. The results show that sections milled with fine drums exhibited a higher skid resistance and macrotexture after milling. The test results also indicate that the forward milling speed is positively associated with both skid resistance and macrotexture. In other words, higher milling speeds tend to produce surfaces with higher skid resistance and macrotexture. The data suggests that milling operations on average provide a service life of about 12 months on seal coats, whereas milling on HMA sections extends the service life beyond 18 months.



## 1. Introduction

A common method to rehabilitate aging asphalt pavements is to remove the upper portion of the existing surface and place a new layer (mill and overlay). This method helps smooth the pavement surface and improve ride. This is usually done with a milling machine, which uses a cutting drum with teeth to remove the asphalt. Pavement texturing is performed by the same milling machines but only removes as little as 3/8 inch off the surface. Different from a typical mill-and-fill operation, no new wearing course is placed after the milling. Instead, the milled surface will already have the desired texture and skid resistance, and can be opened to traffic directly. This procedure is used in Texas as a stop gap measure due to funding or weather constraints before an overlay can be placed on the surface.

### 1.1. Influence of pavement texturing

It has been reported that pavement texturing by milling can improve skid resistance. For example, Yaran and Nesichi [1] showed that the skid resistance of a road section in Israel remained high for more than a year and a half after milling. An Iowa texturing research project [2] showed that the friction number of unmilled sections with AC surfacing averaged 38 while the average friction number of the adjacent milled section of the asphalt surface was up to 44. An Oregon DOT conducted a mill-abrading (combination of mill and shotblast) research project [3], indicating that milling increased the skid number of a PCC pavement from 34 to 39. Another study from Virginia [4] also concluded that pavement skid resistance can be effectively increased by texturing the surface.

Studies also showed that pavement texturing can reduce rutting. For example, Marks [2] found that almost all of the rutting was removed by milling with a cutting depth of 0.5 inch. In another research in Wisconsin [5], average road rut values were reduced for 6 years after milling. Rutting was not significant in the first two

* Corresponding author.
*E-mail address:* lgao5@central.uh.edu (L. Gao).

http://dx.doi.org/10.1016/j.conbuildmat.2015.10.077
0950-0618/

years but became significant at the third year and gradually diminished over the remaining time of the investigation. After 6 years, the surface exhibited rut values almost the same as before the milling.

Texturing by milling also affects the distress and ride quality of pavement. Okpala [5] reported that distress decreased after the pavement was milled. However, this improvement only lasted for less than one year after milling. Their roughness (IRI) results did not indicate any significant difference before and after the milling. It was concluded that the texturing did not improve the ride quality of smoother pavements, even though it was effective in eliminating the rutting.

Researchers have shown that pavement texturing has a short-term effect on road noise levels. Yaran and Nesichi [1] concluded that traveling at high speeds (more than 50 mph) on milled pavements is noisier than unmilled sections. Okpala [5] also found that there was a significant difference in the sound pitch between pre-milled and post-milled sections for a period up to about two weeks after milling, but that the difference became indiscernible after three months. Moreover, there was no significance difference in exterior noise assessment between milled and unmilled sections.

### 1.2. Factors affecting pavement texturing performance

The patterns of a textured surface relies heavily on factors such as milling machine speed, how the drum bits or teeth are located on the cutting drum, and the speed of the cutting drum. Milling operations can be categorized into standard milling, fine milling and micro milling by the number of teeth on the cutting drum [6]:

- Standard milling – Teeth are spaced 5/8 inch apart, 150 bits per drum.
- Fine milling – Teeth are spaced 5/16 inch apart, 300 bits per drum.
- Micro milling – Teeth are spaced 0.2 inch apart, 450–500 bits per drum.

Table 1 provides a summary of existing applications of pavement texturing. In most cases, the micro milling (or fine milling) drum was used. Marks [2] found that texturing using standard milling practices yielded a relatively coarse textured surface that can be detrimental to the safety of motorists.

Studies showed that drum speed and machine forward speed need to be coordinated to produce desired patterns. For example, a report from the Wirtgen Group [7] states that the forward speed should be increased together with the drum speed in order to obtain the same particle size. According to a report from the Asphalt Recycling and Reclaiming Association [8], a reasonable ratio of forward speed to drum speed should be maintained to achieve an acceptable level of quality. The report states that if the forward speed is greater than the drum rotation speed in revolutions per minute (rpm), the machine will produce a very rough textured milled surface. The same research report suggests that the forward speed in feet per minute should not exceed 2/3 of the cutter rpm. Similar findings are also mentioned in an article published by Asphalt Pro Magazine [9], indicating that for 5/8 inch standard mill drum spacing, the best drum speed is around 100 rpm. With a drum speed of approximately 100 rpm, a forward speed of 60 feet per minute (fpm) will provide the optimum pattern. But if the forward speed exceeds 100 feet per minute, the pattern begins to outrun the cut.

Several studies reported on the limit of milling machine forward speeds. For example, an ARRA report [8] states that to achieve a desired texture, the forward speed of the milling machine must be limited. With a standard milling drum, 30 fpm per 100 rpm cutter head speed gives the desired result. For micro milling (or fine milling) drum, a lower value of milling speeds should be used [6]. Marks [2] tested a milling operation with a 411 tooth drum. The forward speed varied from 17 to 28 fpm while the drum speed was a constant 100 rpm. It was found out that the slower the speed the smoother and finer the texture. Another research study in Georgia [10] showed that with a 20 fpm forward speed and 1/16 inch cutting depth, Mean Profile Depth (MPD) values around 0.6 mm can be obtained.

According to ARRA, the milling depth of pavement texturing is usually limited to around 0.4 inch [8]. A TxDOT research project [11] recommended that typical milling cuts to texture flushed pavements range from 0.5 to 0.75 inch maximum. An NCHRP report on pavement friction [12] states that texturing operations typically removes 0.75 to 1.25 inch from the asphalt surface. As shown in Table 1, most of the existing texturing applications use cutting depth from 0.3 to 0.5 inches.

### 1.3. Motivation of this research

Despite the research efforts discussed above, the effects of these milling operation factors (e.g., cutting depth, milling speed, etc.) on the duration of skid improvements have not previously been addressed. It is not clear how different configurations of the machine settings will improve skid and how long that skid improvement lasts. Therefore, in this research study, we conducted pavement texturing tests on various sections across Texas. The skid resistance and macrotexture were measured at each test section for different configurations of milling depths and machine forward speeds. Data were collected during an 18 months investigation period and statistical analysis was conducted to optimize the milling operation.

## 2. Field testing

A number of factors were considered in selecting test sections for evaluation. The most important factors were (1) the availability of the milling machines and pavement sections with the desired skid resistance; (2) the interest and willingness of Texas Districts to assist in evaluating the test sections; (3) the geographical locations and site conditions. The last factor was used to select sections representative of different climatic and surface conditions. At last, 31 test sections (having lengths of 500 feet) were identified in 4 different climatic zones in Texas. While 15 sections have HMA surfaces, the other 16 sections have seal coat surfaces. These sections represent an array of asphalt pavement surface textures with different milling characteristics. The sections are mostly located on 4-lane divided highway facilities.

The literature review indicates that depths of cut up to 0.5 inches are typically used for texturing purposes. Increasing the depth of cut will extend the friction longevity. However, given the surface height variations typically found on both HMA and in particular seal coat surfaces, this parameter cannot be controlled very accurately. Therefore, in this research study, we evaluated two depths of cut (i.e., 0.25 and 0.5 inches).

Two types of milling drums (standard milling drum and fine milling drum) were used in this project. The standard milling drum has in the order of 150 teeth and results in cuts or grooves spaced 5/8 of an inch apart. The fine milling drum with about 300 teeth cuts grooves about 5/16 of an inch apart.

Computer simulations were run to aid the selection of drum rotational speed. Fig. 1 shows the resulting milling patterns for drum speeds of 60, 80 and 100 rpm for a standard milling drum

**Table 1**
Summary of pavement texturing applications.

| Organization | Year | Machine model | Cutting depth | Forward speed | Number of tooth | Drum width | Surface type | Drum speed | Roughness | Skid | Distress | Noise |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Iowa Department of Transportation [2] | 1987 | Wirtgen 1900C | 0.5 inch | 17–28 fpm | 411 | 6.3 ft | AC and PCC | 100 rpm | N.A. | The surface appears relatively tight, but would appear to have enough texture to yield good friction properties | The milling operation removed almost all of the rutting and left a very acceptable texture. | There is some tire noise but it is definitely not objectionable. |
| Nebraska Department of Roads [13] | 2010 | Roadtec RX900 | 0.5 inch | N.A. | 840 | 12.5 ft | N.A. | N.A. | Smooth surface | N.A. | N.A. | N.A. |
| Georgia Department of Transportation [10] | 2009 | N.A. | 1/16 inch | 20 fpm | 500 | 12.5 ft | AC | N.A. | Most of the milled surface for this project had smoothness readings ranging from 650 to 825 mm/km | Surface texture depth (MPD) can reach 1.5 mm | N.A. | N.A. |
| New Zealand [14] | 2006–2012 | Wirtgen 130F | Less than 0.3 inch | N.A. | 300 | 1300 mm (4.3 ft) | N.A. | N.A. | N.A. | Continued improved macrotexture after 2 years | Limitation in creating uniform texture where wheel ruts were present | N.A. |
| Tennessee Department of Transportation [15] | 2011 | N.A. | 0.375–0.5 inch | N.A. | 700–1000 | 12.5 ft | N.A. | N.A. | N.A. | N.A. | N.A. | N.A. |
| Wisconsin Department of Transportation [5] | 1999 | Wirtgen | N.A. | 25 fpm | 500 | 12.5 ft | AC | N.A. | No significant change | N.A. | Reduction in pavement distress index values immediately after milling. The results lasted for a year | Significant change in internal noise for first three months after milling. No change in external noise before and after milling |
| German [16] | 2004 | Wirtgen W2000 | 0.3–0.5 inch | N.A. | 672 | N.A. | AC | N.A. | N.A. | N.A. | Improve driving comfort by minimizing ruts | N.A. |
| Israel [1] | 2001 | N.A. | 0.4 inch | N.A. | N.A. | N.A. | N.A. | N.A. | Increase in roughness | Skid resistance condition of a road section remains high even after more than a year and a half after the treatment | N.A. | More noisy and less convenient |

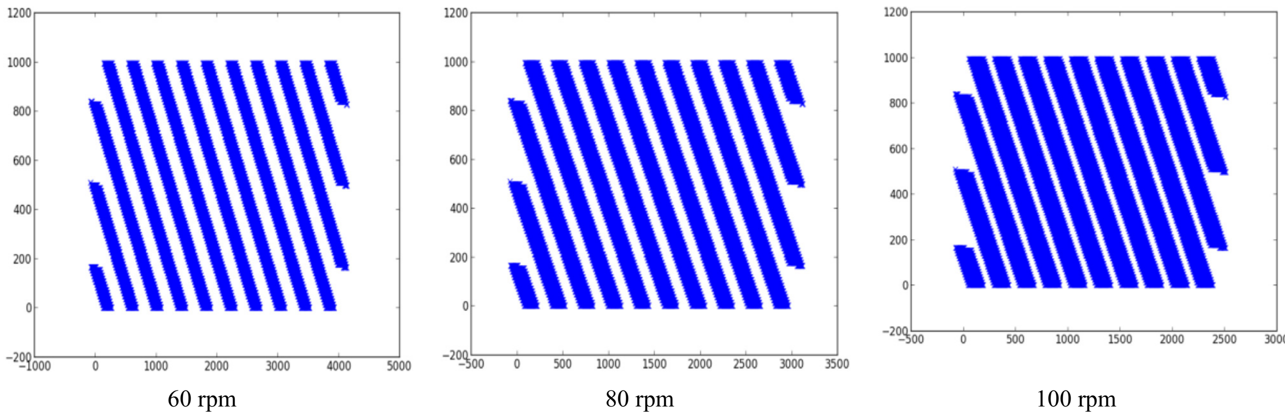



**Fig. 1.** Milling pattern at different drum speed (rpm).

operated at a milling speed of 80 fpm. It can be seen that the variation in drum speed does not significantly impact the milling patterns although at the higher drum speeds the length of the cut is increased, subsequently decreasing the distance between the cuts. Since it might not be possible to vary the drum speeds on the different milling machines used for this study, all milling were done with the drum speed set to 100 rpm – a speed typically used for surface milling.

Milling forward speeds ranging from 30 fpm through 100 fpm were evaluated in this research. An evaluation of the data collected on the sections indicates that friction tends to increase with milling speed. At very high milling speeds (i.e., above 100 fpm), a very rough surface texture was produced that may be detrimental to safety since vehicles and particularly motorcycles may be forced into the longitudinal grooves or tracks produced by milling at these higher speeds. At low speeds, the teeth on the drum made repeated or overlapping cuts in the same groove producing a lower macrotexture. While the surface produced by the lower speeds may result in sufficient texture and improve friction, the low speed of operation is not productive and the friction of the resulting surface may wear rapidly. A computer simulation of the milling process indicated that for a standard milling drum, a speed above 50 fpm is required to prevent overlapping cuts.

The following types of data were collected at each test section:

- Surface Type: hotmix asphalt (HMA) or seal coat.
- Location.
- Climate: dry-freeze, dry-nonfreeze, wet-freeze, and wet-nonfreeze.
- Milling data: milling speed, milling depth, drum type.
- Texture: texture depth measurements, texture measurement device/method.
- Friction: friction measurements, friction equipment/method (device, tire type, test speed).

Both macrotexture and friction tests were done prior to and after milling with subsequent measurements at 3, 6, 12 and 18 month intervals. The following specific texture and friction (skid) tests were used for the selected test sections:

- Texture (macro-texture): CT Meter (ASTM E 2157) Mean Profile Depth (MPD).
  - CT Meter Macrotexture Measurements – Longitudinal and transverse macrotexture measurements were made at three locations in both the left and right wheel paths and the lane center, in accordance with ASTM E 2157.
- Friction:
  - The participating Districts conducted locked-wheel friction testing (ASTM E 274) on each test section and provided the resulting data. All locked-wheel test data were collected around 50 mph using a smooth tire.

Milling and measurements were conducted during the December 2012 to August 2014 time period. Fig. 2 illustrates an example of the resulting surface textures taken at different times of the research.

## 3. Data analysis

A comprehensive statistical analysis of the field measurement was performed to understand the influence of the different milling characteristics and to identify the optimal milling configuration that has potential for delivering long lasting skid resistance.

### 3.1. Deterioration curves

Fig. 3 provides an indication of the durability of macrotexture and skid number for the different forward speeds and surface types based on the texture and friction values obtained during the 18-month research period. The figure illustrates the reduction in texture depth and friction for each test location over time. As shown in the figure, the sections with HMA surfaces exhibited higher levels of texture depth and friction than the sections with a seal coat surface. The HMA surface sections experienced texture depth losses of 0.5 mm and skid number losses of 20 at the time of 18 months after the milling. The sections with seal coat surfaces exhibited texture depth losses of 1.5 mm and skid number losses of 20 over the same time period. The data also illustrates the importance of using forward speed to maintain high levels of friction over time.

### 3.2. Regression analysis

A through statistical analysis was conducted to remove the random noise of the field measurements collected at different time intervals and to develop valid recommendations. As part of this study, the influence of forward milling speed, milling drum type and milling depth on the deterioration of macrotexture and skid resistance of milled surfaces was investigated. The seal coat and hot mix asphalt (HMA) sections tested were treated separately, although the statistical analysis was performed simultaneously to achieve higher statistical power. Separate statistical models were


**Fig. 2.** Photos taken at a test section.

estimated for understanding the influence of the milling characteristics on deterioration of the milled surfaces in terms of reductions in macrotexture and skid resistance. The statistical methodology employed for the model development and a discussion on the modeling results are provided below.

### 3.2.1. Model development

The researchers employed multiple linear regression analysis for statistical inference on which milling guidelines and recommendations will be developed. Multiple linear regression is a technique that attempts to model the relationship between two or more explanatory variables and a response variable by fitting a linear equation to observed data. The measured surface properties, macrotexture and skid resistance are modeled as continuous dependent variables. The milling characteristics such as milling drum type, pavement surface type (HMA or seal coat) and milling depth are incorporated into the statistical analysis as categorical variables. The forward milling speed is introduced into the analysis as a continuous variable. The field data was collected at multiple times during the analysis period of 18 months: before and immediately after milling, 3, 6, 12 and 18 months after the milling. The time of the measurement (in months) is also incorporated into the statistical analysis to model the rate of deterioration. Additionally, the influence of the milling characteristics on the deterioration of skid resistance and macrotexture is also evaluated by incorporating explanatory variables that allow for the interaction of milling features over time. It is important to note that the statistical analysis does not include the measurements collected before the milling operation as the main objective of the statistical analysis is to model the deterioration of the surface properties. The regression model that is being estimated in this study is presented below:

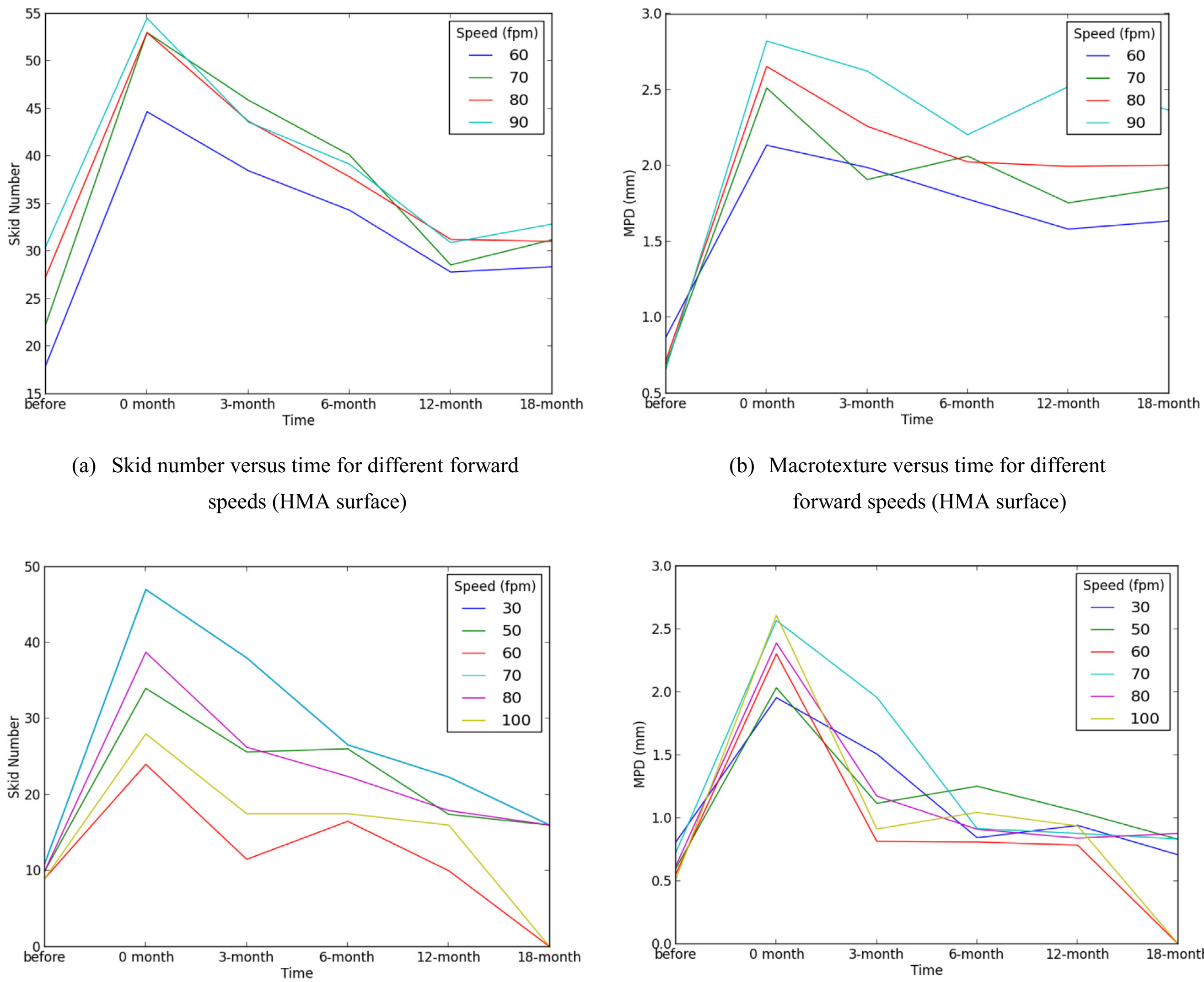
$$Y_{it} = \beta_0 + \beta_1 \times I_{Seal\ Coat} + \beta_2 \times I_{Fine\ Drum} + \beta_3 \times I_{Milling\ Depth} + \beta_4 \times I_{Left\ Wheel\ Path} + \beta_5 \times I_{Right\ Wheel\ Path} + \alpha_1 \times t + \alpha_2 \times S + \delta \times Z + \varepsilon_{it}$$

where,

$Y_{it}$ = The *i*th observation of the surface property measured at *t*th time period. It can be skid resistance or macrotexture.
$I_{Seal\ Coat}$ = Indicator variable that takes a value of 1 for seal coat sections.
$I_{Fine\ Drum}$ = Indicator variable that takes a value of 1 for sections milled with a fine drum.
$I_{Milling\ Depth}$ = Indicator variable that takes a value of 1 for sections milled to a depth of 0.2 inch.
$I_{Left\ Wheel\ Path}$ = Indicator variable that takes a value of 1 for measurements on the left wheel path.
$I_{Right\ Wheel\ Path}$ = Indicator variable that takes a value of 1 for measurements on the right wheel path.
$S$ = Forward milling speed (fpm).
$t$ = Time of measurement.
$Z$ = Vector of interaction variables of the time and the milling features.
$\beta_0$ = Intercept term.
$\beta_1$ to $\beta_5$ and $\alpha_1$ to $\alpha_2$ = Regression coefficients.
$\delta$ = Vector of regression coefficient corresponding to the interaction terms.
$\varepsilon_{it}$ = Idiosyncratic error term.

### 3.2.2. Analysis results

The final model specifications were chosen carefully based on a rigorous model development process including all the aforementioned variables. Subsequently, model refinement was carried out using statistical tests such as F-test and exclusion of statistically insignificant variables at the 95% confidence level. Intuition and engineering judgment played a role in the removal of statistically insignificant variables, rather than solely adopting a statistically based mechanical approach. Tables 2 and 3 show the statistically significant multiple linear regression model coefficient estimates along with their standard deviations corresponding to both skid resistance and macrotexture respectively.




(a) Skid number versus time for different forward speeds (HMA surface)

(b) Macrotexture versus time for different forward speeds (HMA surface)

(c) Skid number versus time for different forward speeds (seal coat surface)

(d) Macrotexture versus time for different forward speeds (seal coat surface)

**Fig. 3.** Friction and macrotexture deterioration curves.

**Table 2**
Model estimation results for skid resistance.

| Covariate description | Estimate | Std. error | *t* value | *P*-value |
|---|---|---|---|---|
| Intercept | 34.63 | 2.90 | 11.95 | 0.00 |
| Indicator: Seal coat | −14.04 | 3.31 | −4.25 | 0.00 |
| Indicator: Fine drum | 20.58 | 1.16 | 17.78 | 0.00 |
| Speed (ft/min) | 0.17 | 0.04 | 4.42 | 0.00 |
| Time (in months) | −1.12 | 0.06 | −17.70 | 0.00 |
| Interaction: Seal coat × time | 0.29 | 0.14 | 2.14 | 0.03 |
| Interaction: Seal coat × speed | −0.14 | 0.04 | −3.36 | 0.00 |
| Interaction: Fine drum × time | −0.80 | 0.14 | −5.60 | 0.00 |

**Table 3**
Model estimation results for macrotexture.

| Covariate description | Estimate | Std. error | *t* value | *P*-value |
|---|---|---|---|---|
| (Intercept) | 0.72 | 0.296 | 2.43 | 0.02 |
| Indicator: Seal coat | 0.84 | 0.333 | 2.51 | 0.01 |
| Indicator: Fine drum | 0.19 | 0.081 | 2.32 | 0.02 |
| Speed (ft/min) | 0.02 | 0.004 | 5.53 | 0.00 |
| Time (in months) | −0.03 | 0.006 | −4.27 | 0.00 |
| Interaction: Seal coat × time | −0.05 | 0.009 | −5.17 | 0.00 |
| Interaction: Seal coat × speed | −0.02 | 0.004 | −4.50 | 0.00 |

Overall the modeling results indicate that both skid resistance and macrotexture deteriorated over time on all the sections. This is evident from the negative sign on the coefficients corresponding to time in both Tables 2 and 3. The data suggests that milling speed and milling drum type were governing the deterioration of skid resistance and macrotexture. It should be noted that depth of milling did not significantly influence the deterioration of either skid resistance or macrotexture.

*3.2.3. Synthesis of analysis results*

The positive and negative signs of the coefficients in Tables 2 and 3 indicate the effect of the influence variable on skid resistance and macrotexture. In the case of indicator variables this influence is expressed relative to reference variables. A positive sign indicates that the variable contributes to an increase in skid resistance or macrotexture whereas a negative sign indicates that the variable contributes to a decrease. Thus, for example, the negative sign on the coefficient corresponding to the seal coat indicator variable

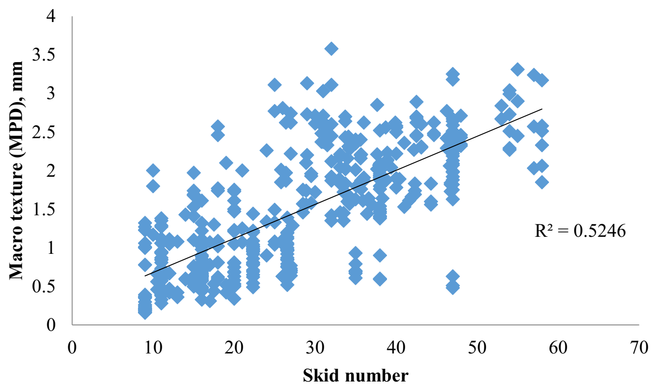



**Fig. 4.** Skid number versus macrotexture after milling.

shown in Table 2 (i.e., −14.04) indicates that, on average, the seal coat sections exhibited a lower skid resistance relative to that of the HMA sections (reference) after milling, while keeping other variables unchanged or under similar conditions. Based on the skid resistance measurements collected prior to the milling operation, the selected pool of seal coat sections exhibited much lower skid resistance prior to milling. This explains the observed lower skid resistance on the seal coat projects after milling.

A higher macrotexture was evident on the seal coat sections relative to that of HMA sections after milling on average. This is indicated by a positive sign on the coefficient corresponding to the seal coat indicator variable (i.e., 0.84) shown in Table 3. Although seal coats exhibited higher macrotexture relative to HMA, the skid resistance was larger on the HMA sections after milling. This can be attributed to the lack of correlation between the macrotexture and skid resistance results suggesting that a higher macrotexture does not always reflect a higher skid resistance. Fig. 4 shows a scatter plot between the macrotexture and skid resistance measurements on the sections evaluated as part of the study. Despite the positive correlation, it can be seen that macrotexture and skid resistance are only moderately related. Serigos et al. [17] also reported a lack of correlation between macrotexture and skid resistance. They emphasize the collective role of macrotexture and microtexture on skid resistance.

The deterioration in macrotexture and skid resistance was observed to be different on seal coats and HMA pavement surfaces. The positive sign on the coefficient corresponding to the interaction variable: seal coat × time in Table 2 (i.e., 0.29) indicates that the rate of loss of skid resistance is lower on seal coats than on HMA sections and that the HMA sections lose an additional 0.29 skid number per month compared to seal coat surfaces. This same interaction variable in Table 3 indicates that HMA surfaces lose macrotexture faster than the seal coat sections. This could also be attributed to the lack of adequate correlation between macrotexture and skid resistance. Figs. 5 and 6 show the deterioration trends of skid resistance and macrotexture corresponding to both HMA and seal coats. These deterioration trends were evaluated in more detail to ascertain the influence of drum type and milling speed.

*3.2.3.1. Influence of drum type.* The positive sign of the coefficient corresponding to the fine drum indicator variable indicates that

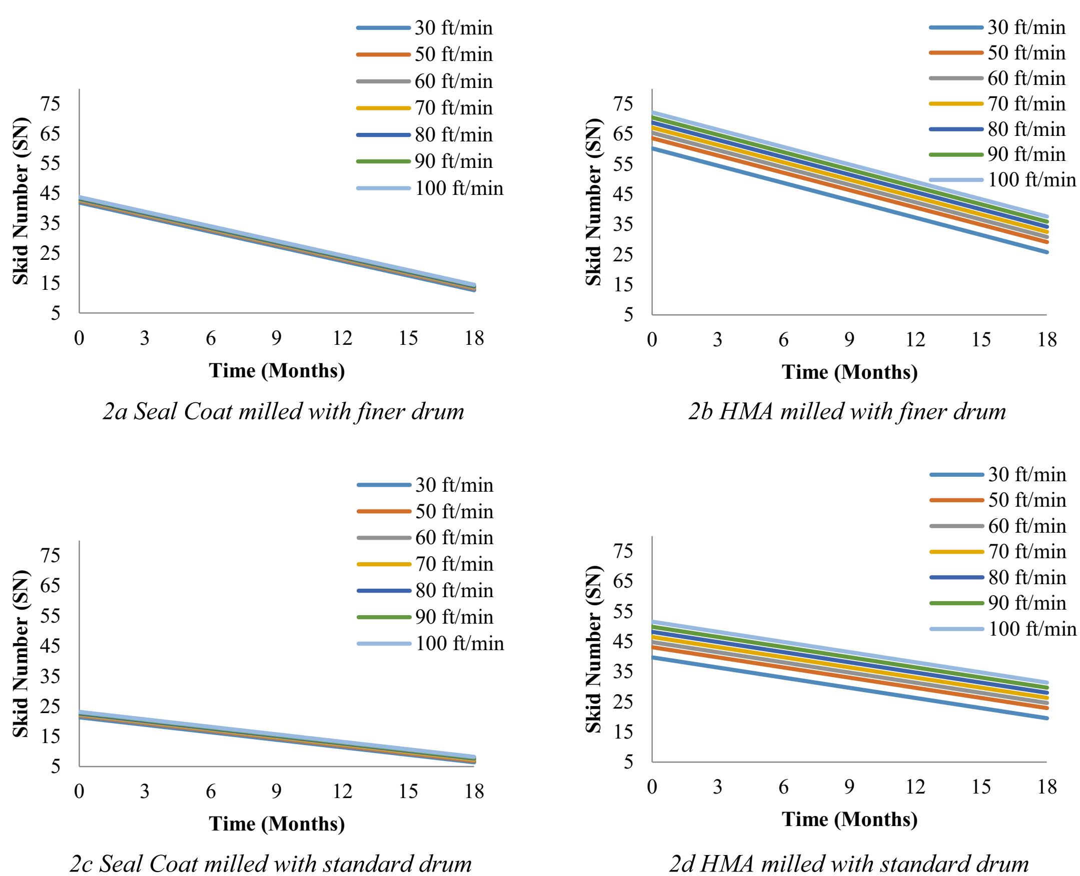



**Fig. 5.** Deterioration of skid resistance based on the regression model.

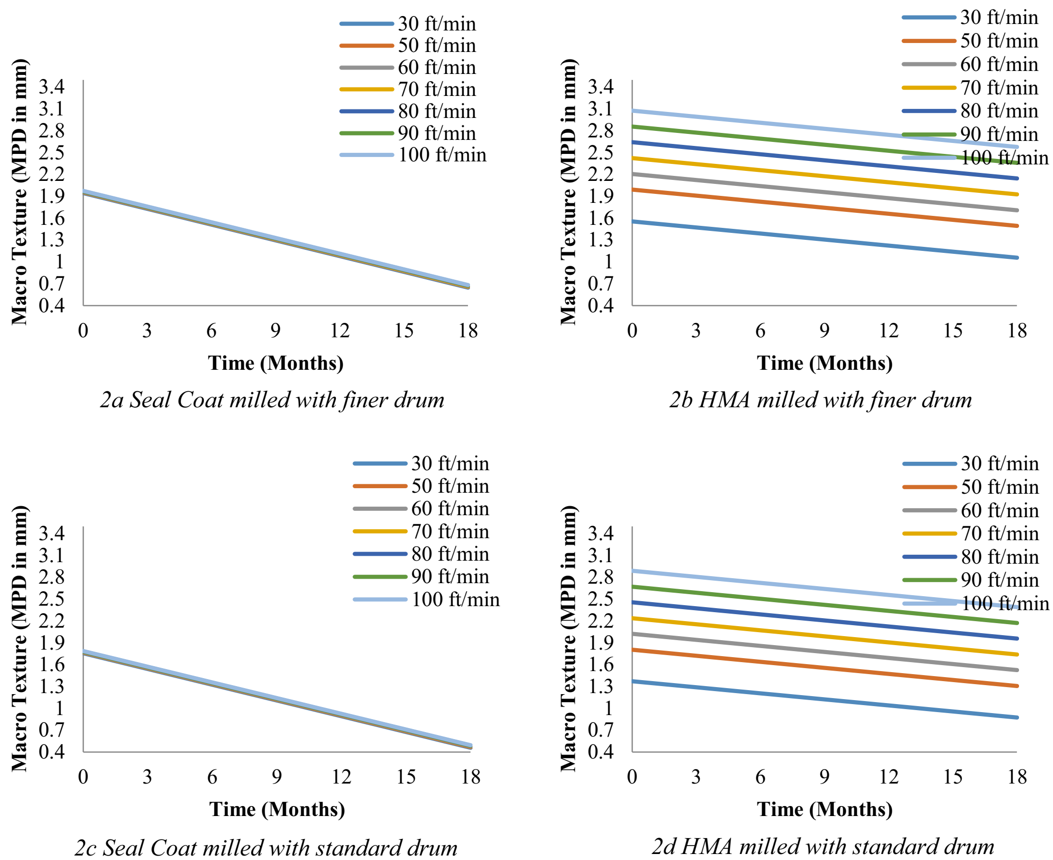



**Fig. 6.** Deterioration of macrotexture based on the regression model.

sections milled with fine drums exhibited a higher skid resistance after milling as shown in Table 2. The data suggests an average positive skid number difference of 20.58 between the sections milled with finer drums and the sections milled with standard drums, while keeping the other factors unchanged. These data are somewhat misleading though as the sections milled with the finer drums had consistently higher initial skid resistance than the sections milled with the standard drums.

The macrotexture model shown in Table 3 also emphasized the benefits of milling operations with finer drums relative to the standard drums in terms of macrotexture improvement. The positive sign of the coefficient corresponding to the fine drum indicator variable indicates that sections milled with fine drums exhibited a higher macrotexture over time. An average difference in Mean Profile Depth (MPD) of 0.19 was evident after milling, assuming that all other factors remain unchanged.

It is interesting to note that the rate of deterioration of skid resistance is higher in the case of seal coat and HMA sections milled with finer drums relative to that of standard drums. This suggests that finer drums should preferably not be used on sections with initial lower skid resistance.

*3.2.3.2. Influence of forward milling speed.* The modeling results shown in Tables 2 and 3 indicate that the forward milling speed is positively associated with both skid resistance and macrotexture. In other words, higher milling speeds tend to produce surfaces with higher skid resistance and macrotexture. The results suggest that seal coats are not as sensitive as the hot mix sections to the forward milling speed in terms of improving skid resistance and macrotexture. Higher milling speed is clearly more beneficial on HMA surfaces than on seal coats. This is also illustrated in Figs. 5 and 6. The deterioration trends corresponding to different speeds are separated by a vertical shift in the case of HMA sections. On the other hand, the deterioration trends of the seal coat sections are overlapping. The results thus highlight the benefits of employing higher milling speeds, particularly on the HMA sections.

While the results indicate the benefits of high milling speeds, practical limits should be imposed on these speeds as very high milling speeds produce surfaces that tend to be noisy and potentially create adverse conditions for motorcyclists in particular. Thus a maximum forward milling speed that ensures adequate skid resistance without adversely effecting pavement noise and safety should be employed.

*3.2.3.3. Service life.* An analysis of the skid resistance measurements over time on the sections evaluated as part of the study indicate that milled seal coats deteriorate more rapidly than HMA sections. The data suggests that milling operations on average provide an additional service life of about 12 months on seal coats, whereas milling on HMA sections extends the service life beyond 18 months. Linear extrapolation of the skid number data on the HMA sections indicate that these values would fall below 20 after about 2 years.

## 4. Conclusions and recommendations

Data analysis was performed on the skid resistance and macrotexture data collected on the seal coat and HMA sections over time. These data were collected before and immediately after milling of the sections and again after 3, 6, 12 and 18 month intervals. The following conclusions were drawn from this study:

- Data processing and regression analysis of texture and friction measurement data collected on all test sections, combined with other pertinent available test section data (e.g., surface type, climate data, and equipment data), indicated that skid resistance is influenced to a large extent by surface type, milling drum type and machine milling speed. The depth of milling employed does not appear to significantly influence either the surface texture or skid resistance of seal coat and HMA sections.
- Skid resistance and texture depth can become inadequate quickly (within a year) if extensive bleeding is observed at time of the milling.
- Based on extensive skid resistance and macro-texture testing and available equipment information, the use of higher milling machine forward speed helps create the texture qualities needed for higher level friction on HMA surface. Although the speeds of 90 and 100 fpm can produce the highest levels of skid resistance on the test sections, they are highly prone to creating objectionable grooves to the motorcyclists. Forward speeds of 70–80 fpm can result in less detrimental effects of pavement texture on motorcycle handling and can significantly improve skid resistance. However, seal coats are not influenced by milling speed to the same extent as HMA, which appear to perform better over time when milled at higher speeds.
- Pavement texturing appears to improve the skid resistance of road sections and extend the corresponding service life of seal coat surface sections by 12 months. The textures of HMA surface evaluated in this study showed relatively high skid resistance at the time of 18 months after the milling. Linear extrapolation of the skid number data on the HMA sections indicate that these values would fall below 20 after about 2 years.
- It was found that sections milled with finer milling drums appear to perform better than those milled with standard drums, providing improved macrotexture and skid resistance after 18 months. A higher rate of deterioration in skid resistance and macrotexture was found, however, for sections milled with finer drums.

Based on the statistical analysis of the skid resistance and macrotexture data measured on the seal coat and HMA sections evaluated as part of the study, the following pavement texturing guidelines are recommended:

1. Finer milling drums are recommended over standard milling drums if the sections have higher initial skid resistance (above 25 SN).
2. A forward milling speed of 70–80 feet per minute is recommended.
3. A depth of milling cut between 0.25 and 0.5 inches may be used on both seal coat and HMA sections.

## Acknowledgments

This study was funded by Texas Department of Transportation Project 0-6752. The authors would like to thank all Texas Department of Transportation personnel who contributed to this research study. All opinions, errors, omissions, and recommendations in this paper are the responsibility of the authors.

## References

[1] R. Yaran, S. Nesichi, Alleviating the Skid Resistance Problem – The Israeli Experience, Public Works Department, Israel, 2005.
[2] V.J. Marks, Pavement Texturing by Milling, Iowa Highway Research Board, 1987.
[3] L. Hunt, Millabrading Test Evaluation, Oregon Department of Transportation, 1999.
[4] D.C. Mahone, C. Sherwood, The effect of Aggregate Type and Mix Design on the Wet Skid Resistance of Bituminous Pavement: Recommendations for Virginia's Wet Accident Reduction Program, Virginia Department of Transportation, 1995.
[5] D. Okpala, Fine Tooth Milling Treatment of Rutted Asphaltic Concrete Pavements, Wisconsin Department of Transportation, 1999.
[6] Micro-milling – The finer side of milling, Pavement interactive, [Online] 9 20, 2011, <http://www.pavementinteractive.org/2011/09/20/micro-milling-the-finer-side-of-milling/>.
[7] Improved components for the milling and mixing process, Wirtgen, [Online] [Cited: 12 25, 2012] <http://www.cimne.com/paramix/pdf/Deliverable_5-1.pdf>.
[8] L. Dunn, S. Cross, Basic Asphalt Recycling Manual, Asphalt Recycling and Reclaiming Association, 2011.
[9] Asphalt Pro Magazine, Optimize drum RPMs for best cutting pattern, [Online] [Cited: 12 20, 2012].
[10] , J. Lai, M. Bruce, D.M. Jared, P. Wu, S. Hines, Georgia's evaluation of surface texture, interface characteristics and smoothness profile of milled surface, Transportation Research Board Annual Meeting, 2009.
[11] M. Leaverton, S. Senadheera, W.D. Lawson, Short Term Solutions to Bleeding Asphalt Pavements, Texas Department of Transportation, 2006.
[12] J.W. Hall, K.L. Smith, L. Glover Titus, J.C. Wambold, T.J. Yager, Z. Rado, Guide for Pavement Friction, National Cooperative Highway Research Program (NCHRP), Transportation Research Board of the National Academies, 2009.
[13] When more teeth make quick work, <http://www.forconstructionpros.com>, [Online] 12 13, 2010, <http://www.forconstructionpros.com/article/10288520/when-more-teeth-make-quick-work>.
[14] Higgins, Extending surfacing life with fine milling, [Online] [Cited: 12 5, 2012] <http://www.roadingnz.org.nz/sites/roadingnz.org.nz/files/AAG-Clarke_Extending_Surfacing_Life.pdf>.
[15] The growth of micromilling, <http://www.forconstructionpros.com>, [Online] 11 30, 2011, <http://www.forconstructionpros.com/article/10456001/the-growth-of-micromilling>.
[16] Fine milling for more economical placement of thin cold layers, <http://www.wirtgen.de>, [Online] [Cited: 12 5, 2012] <http://www.wirtgen.de/en/aktuelles_und_presse/presseberichte/presse_detail_443.html>.
[17] P. Serigos, A. Smit, J. Prozzi, Incorporating surface microtexture in prediction of skid resistance of flexible pavements, in: CD Proceedings of the Transportation Research Boards' 93rd Annual Meeting, Washington, D.C., 2014.