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Short-Term Skid Improvements by Light Texturing with a Milling Machine

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16. Abstract

Skid problems on roads can result from flushing and bleeding where excessive road-mix binder can accumulate on a road’s surface as well as general wear of the surface by traffic. This may result in a polished surface that may increase the chances of accidents due to the reduced skid resistance. Strategies to address this problem include mill and fill or overlay rehabilitation but another cost effective solution is to remove only the top portion of the surface course using light-texturing or micro-milling. Unlike a typical mill-and-fill operation, there is not an additional step in laying a new wearing course after milling has been completed. Instead, the newly exposed surface will already have the desired final texture and noise properties, and can be opened to traffic sooner. Some Texas districts have already implemented this technology and have achieved substantially improved skid resistance and reduced rutting with no detrimental effects to the existing pavement. However, these texturing improvements have not been studied to determine how well they improve skid and how long that skid improvement lasts.

In this research, light texturing of pavement had been conducted at thirty one sections across Texas. The research team visited each test section during the milling and used different configurations of milling depths and machine forward speeds. While Sand Patch Test, Circular Track Meter and 3D laser scanner were used to obtain the pavement surface texture, British pendulum and skid truck were used to obtain the skid resistance before the milling and at 0, 3, 6, 12 and 18 months after the milling. The tests are repeated 3 times at every test section for better accuracy. The Mean profile depth value is measured for left wheel path, right wheel path and middle wheel path. 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 light 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.

17. Key Word
Light Texturing, Skid Resistance, Pavement Texture, Milling Machine

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by

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Research Project 0-6752

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Performed in Cooperation with the
Texas Department of Transportation and the
Federal Highway Administration

Disclaimer

This research was performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration. The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. Trade names were used solely for information and not product endorsement.

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Chapter 1. Literature Review

1.1 Background of Light Texturing

A common technique when rehabilitating aging asphalt pavements is to mill off a portion of the existing surface before placing a fresh layer. This process helps eliminate irregularities in the pavement surface and restore ride. This is done with a milling machine, which uses a large drum with carbide tipped teeth to remove the asphalt. Light texturing is performed by the same milling machines but just removes as little as 3/8 inches off the surface. Unlike a typical mill-and-fill operation, there is not an additional step in laying a new wearing course after milling has been completed. Instead, the newly exposed surface will already have the desired final texture and noise properties, and can be opened to traffic sooner. After light texturing, the macrotexture mean depth obtained by the sand patch method is close to 2 millimeter (1). The smoothness of a finished light texturing surface relies heavily on factors such as milling machine speed, how teeth are located on the cutting drum, and the speed (RPMs) of the cutting drum. The following sections discuss those technical issues and the effects of light texturing on pavement skid resistance, roughness, distress and noise.

1.1.1 Number of Drum Teeth

A few categories of milling exist that are defined by the teeth on the cutting drum used (2):

- Standard milling – Teeth are spaced 5/8 in (15mm) apart, 150 bits
- Fine milling – Teeth are spaced 5/16 in (8mm) apart, or approximately twice as many bits, 300 bits
- Micro milling – Teeth are spaced 0.2 in (5mm) apart, or approximately three times as many bits, 450-500 bits

In most of the existing applications of light texturing, the micro milling (or fine milling) drum (Figure 1) is used. According to a research by Iowa Highway Research Board (3), the light texturing using standard milling practices yielded a relatively coarse textured surface that is objectionable to a substantial number of motorists.

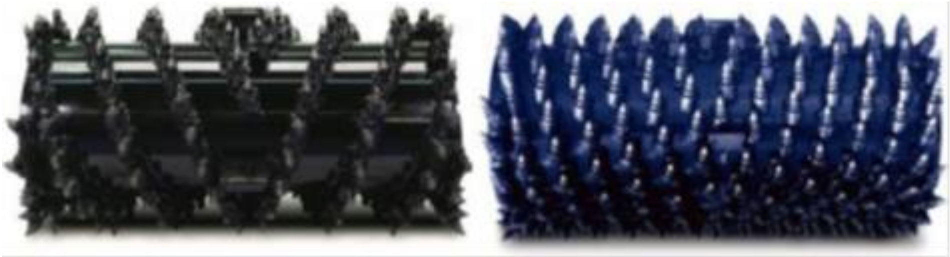


Figure 1. Standard Milling and Micro Milling Drums (4)

Because of the spacing and number of teeth on the milling drum, micro milled surfaces are distinct from their traditionally milled counterparts. Figure 2 illustrates the surface texture by using different milling drums.

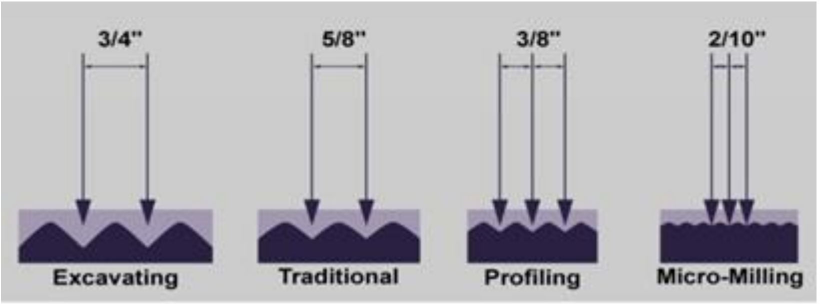
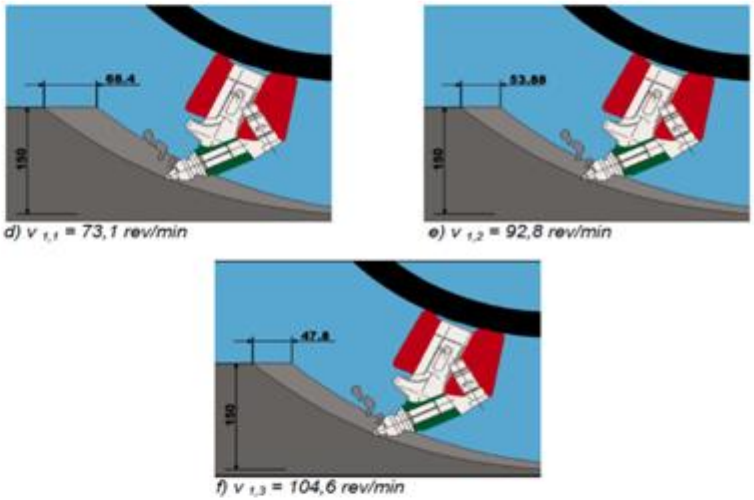


Figure 2. Drum Tooth Spacing and Texture (5)

1.1.2 Machine forward speed and drum speed

A study conducted by Wirtgen Group (6) shows that while increasing the drum speed, the forward speed should also be increased in order to obtain the same particle size. Figure 3 shows the effect of varying drum speed on the texture while keeping the forward speed constant. According to Asphalt Recycling and Reclaiming Association (7), a reasonable ratio of forward speed to drum speed should be maintained to achieve an acceptable level of quality. If the forward speed in feet is greater than the drum RPM, the individual cutting tools will not be overlapping their adjacent cut, which will lead to a very rough textured milled surface. To maintain an acceptable level of production and quality, it was recommended by this research that the forward speed in feet per minute should not exceed 2/3 of the cutter RPM. For example, when the drum works at 100 RPM, a 66 feet (20 m) /minute travel speed will allows 1/3 overlap in cutting between adjacent teeth. This result was also mentioned in an article published by Asphalt Pro Magazine (8). The author claimed that for 5/8-inch standard mill drum spacing, the best drum speeds is around 100 RPM. With a drum speed of approximately 100 RPM and a forward speed of 0 to 60 fpm, the pattern behind the mill is optimum. With a drum speed of approximately 100 RPM and a forward speed of 60 to 100 feet per minute the pattern behind the mill is generally acceptable. But if the forward speed exceeds 100 feet per minute, the pattern begins to outrun the cut.



d) $v_{1,1}$ = 73,1 rev/min

e) $v_{1,2}$ = 92,8 rev/min

f) $v_{1,3}$ = 104,6 rev/min

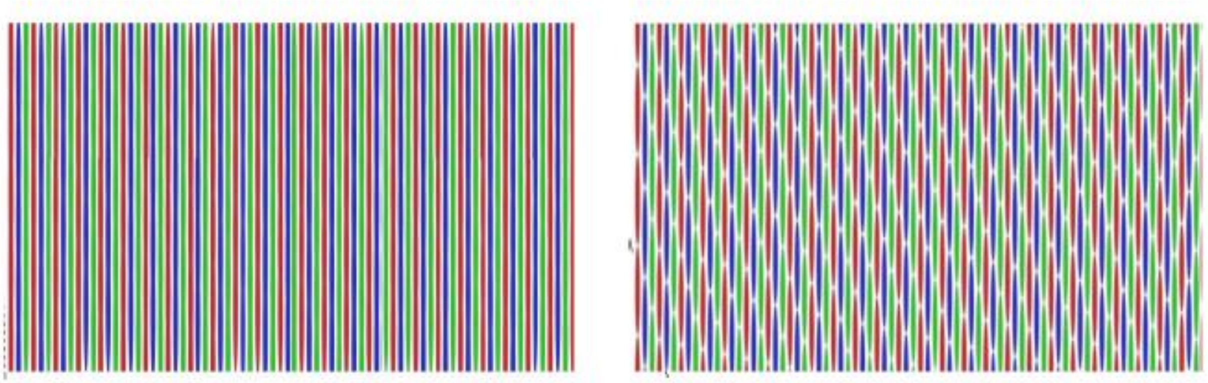
Figure 3. Schematic showing the simulation of varying the milling drum speed while keeping the machine forward speed constant (6)

1.1.3 Forward Speed and Texture

According to Asphalt Recycling and Reclaiming Association (7), to achieve a very good even texture, the forward speed of the milling machine must be limited. With a standard milling drum, 9 meter per minute (30 fpm) per 100 RPM cutter head speed gives the desired result. For micro milling (or fine milling) drum, a lower range of traditional milling speeds should be used to meet smoothness requirements (2). An Iowa light texturing research project tested a milling operation with 411 tooth drum (3). The forward speed varied from 17-28 ft per minute 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 in Georgia (9) showed that with 20/ft forward speed and 1/16 in cutting depth, Mean Profile Depth (MPD) values around 0.60 mm can be obtained (Figure 5). The simulated surface texture using different forward speeds can be found in Figure 4.

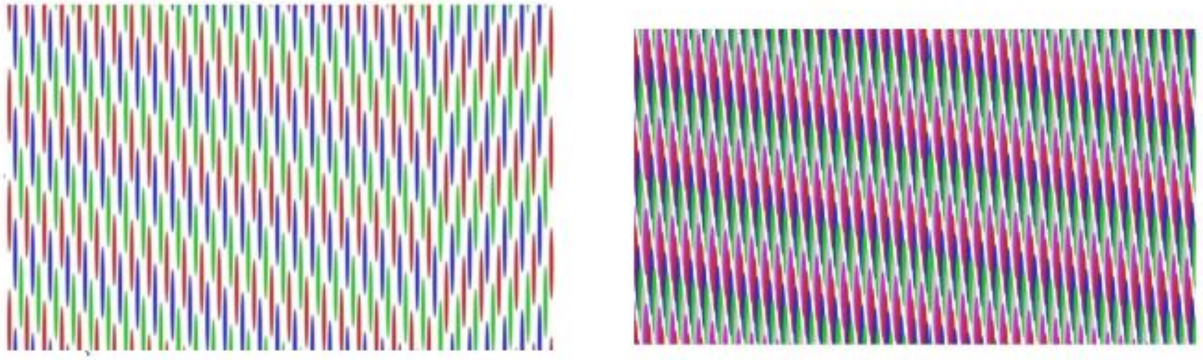
1.1.4 Milling depth

The milling depth of light texturing is usually limited to around 0.4 inches and the milled surface can be opened to traffic with no further treatment (7). TxDOT research project 0-5230 (10) recommended that typical milling cuts for light texturing treatment of flushed pavements range from 1/2 to 3/4 inch maximum. A NCHRP report on pavement friction (11) states that light texturing operation typically removes 0.75 to 1.25 in (19 to 32 mm) from the asphalt surface. As shown in Table 1, most of the existing light texturing applications use cutting depth from 0.3 to 0.5 inches.



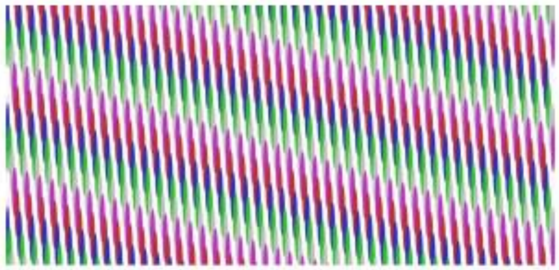
a. 20 Feet per Minute Forward Speed with Standard Spaced Drum

b. 60 Feet per Minute Forward Speed with Standard Spaced Drum



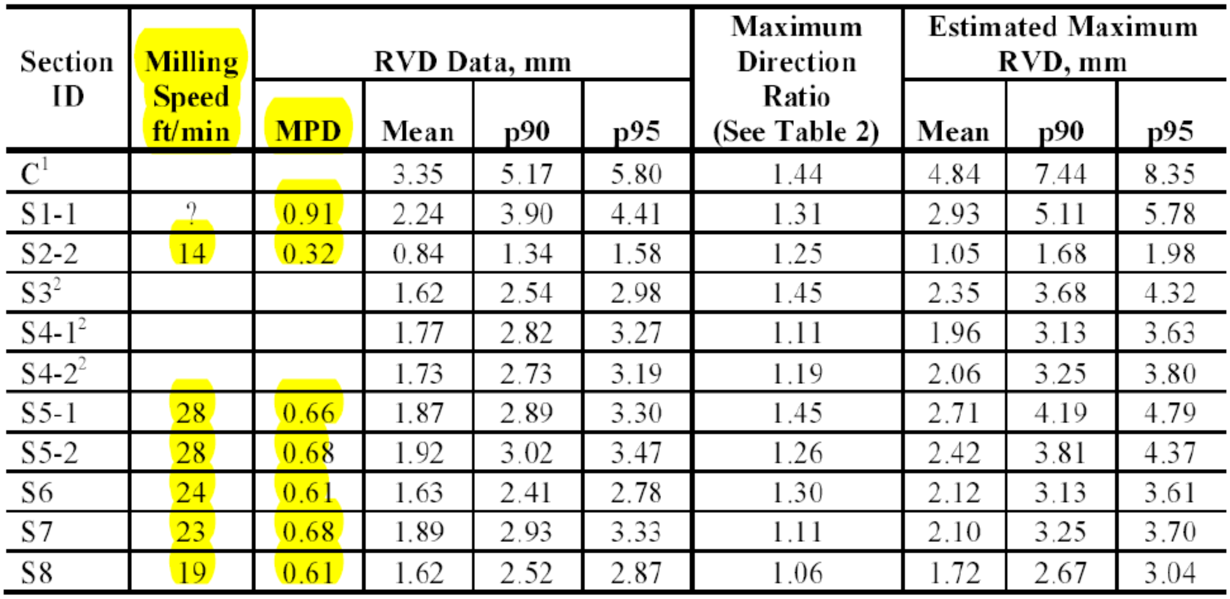
c. 100 Feet per Minute Forward Speed with Standard Spaced Drum

d. 60 Feet per Minute Forward Rate with Fine Milling Drum



e. 100 Feet per Minute Forward Rate with Fine Milling Drum

Figure 4. Texture Pattern and Forward Speed (12)



Section ID	Milling Speed ft/min	RVD Data, mm				Maximum Direction Ratio (See Table 2)	Estimated Maximum RVD, mm		
		MPD	Mean	p90	p95		Mean	p90	p95
C[1]			3.35	5.17	5.80	1.44	4.84	7.44	8.35
S1-1	?	0.91	2.24	3.90	4.41	1.31	2.93	5.11	5.78
S2-2	14	0.32	0.84	1.34	1.58	1.25	1.05	1.68	1.98
S3[2]			1.62	2.54	2.98	1.45	2.35	3.68	4.32
S4-1[2]			1.77	2.82	3.27	1.11	1.96	3.13	3.63
S4-2[2]			1.73	2.73	3.19	1.19	2.06	3.25	3.80
S5-1	28	0.66	1.87	2.89	3.30	1.45	2.71	4.19	4.79
S5-2	28	0.68	1.92	3.02	3.47	1.26	2.42	3.81	4.37
S6	24	0.61	1.63	2.41	2.78	1.30	2.12	3.13	3.61
S7	23	0.68	1.89	2.93	3.33	1.11	2.10	3.25	3.70
S8	19	0.61	1.62	2.52	2.87	1.06	1.72	2.67	3.04

Figure 5. Milling speed and Macrotexture MPD (9)

1.1.5 Influence of light texturing on skid resistance

In the Israel light texturing research project, Yaron and Nesichi (1) showed that the skid resistance condition of a road section remains high even after more than a year and a half after the treatment. In the Iowa light texturing research project (3), the result shows that the average friction number of the unmilled adjacent sections with AC surface averaged 38. The average friction number of the milled section of the asphalt surface was 44. The average friction number of the unmilled, adjacent section with PCC surface was 37. The milled section of this PCC yielded an average friction number of 50. In the Oregon DOT conducted millabrading (combination of mill and shotblast) research project (13), the results shows that the milling increased the skid number of the PCC pavement from 34 to 39 in the center lane. With the shot blasting, the center lane skid number increased from 39 to 47. Skid numbers, however, have continued to decline, returning to near the preconstruction skid numbers (Figure 6). Another study from Virginia (14) concluded that pavement skid resistance can be effectively increased by light texturing. However, the research result also pointed out that mix design may be critical to the long term success of textured pavements. High density and high asphalt content resulting in an unstable mix were suspected as the causes for the rapid skid reversion. Lower density, lower asphalt content and an adequate void structure may have been important factors in retaining pavement texture and skid resistance.

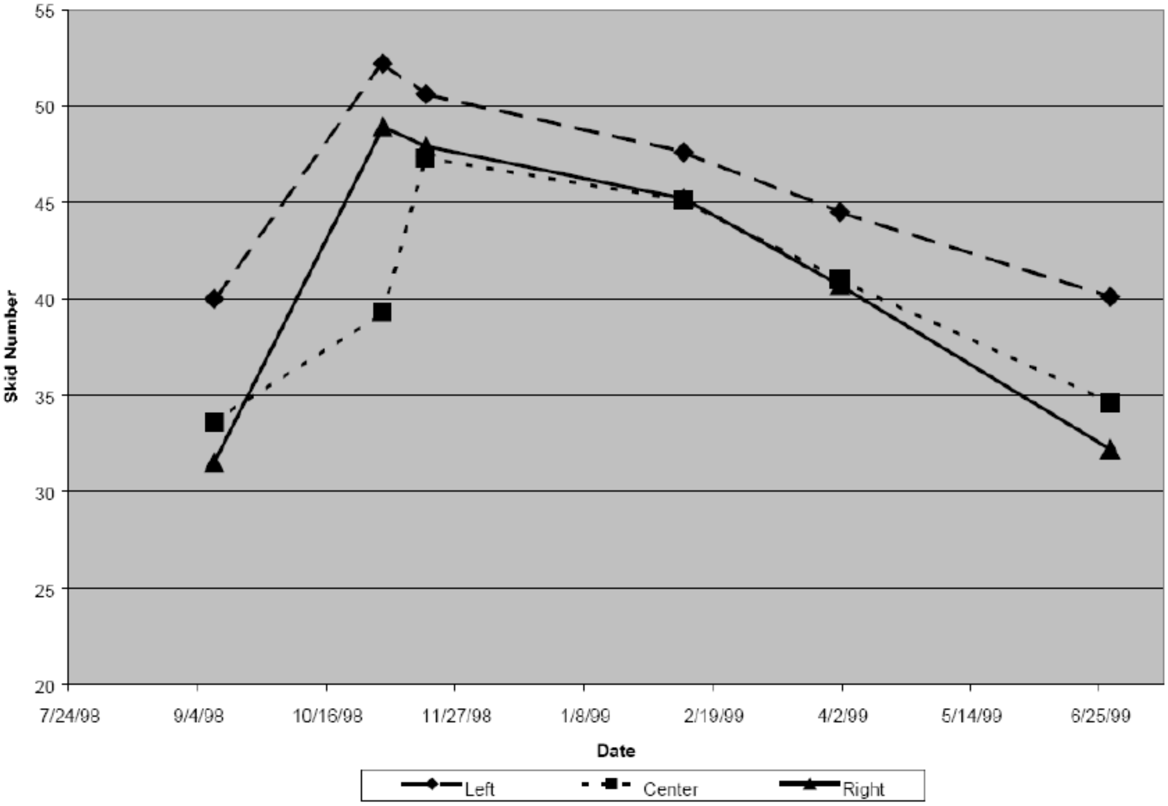


Figure 6. Friction testing result in Oregon

1.1.6 Influence of light texturing on rutting

In the Iowa light texturing project (3), almost all of the rutting was removed by removing ½ in. from the milled section with cutting depth of ½ inch. In the light texturing research project conducted in Wisconsin (15), road rut values were recorded for six years after the milling. These values are the average rut measurements of each wheel path (Left Wheel Path and Right Wheel Path). Rutting was insignificant for the first two years after milling. However, it became significant from the third year and progressively deteriorated through the end of the investigation. After six years in service, the milled surface exhibited rut values almost as high as those obtained prior to the milling operation.

1.1.7 Influence of light texturing on distress and ride

The Wisconsin project (15) showed that the pavement distress decreased after the pavement was milled. However, this reduction lasted for less than one year after milling. By the second year, the distress values were similar to those obtained prior to milling and progressively increased up to the end of the investigation. The IRI results do not indicate any significant difference before and after the milling. Also there is no significant change in the IRI with age. It was concluded by the researchers that light texturing did not improve the ride quality of a pavement that already rode good, even though it was effective in eliminating the rutting in the pavement.

1.1.8 Influence of light texturing on noise

The Israeli research project (1) showed that the texture obtained by light texturing was rougher than the other retexturing methods. Traveling at high speeds (more than 50 mph) on these pavements is noisier and less convenient. The Wisconsin project (15) found that there was a noticeable difference in the sound pitch between the pre-milled and post-milled conditions for a period up to about two weeks after milling, while the change in loudness (dB) appears to be insignificant. However, results taken after three months did not indicate any discernible pitch change. Exterior dBA levels did not indicate any significant difference between the pre-milled and post-milled condition. Also, a subjective exterior noise assessment showed that no significant difference existed between milled and non-milled lanes (driving and passing lanes respectively) as the vehicles passed through the test sections.

1.2 Light Texturing Applications

In this literature review, the research team gathered and summarized information regarding to the best practice of light-texturing application by other transportation agencies. Table 1 presents the summary of those applications.

1.2.1 Iowa Department of Transportation

In 1987, Iowa Department of Transportation conducted a research to study the effect of micro-milling on asphalt concrete and portland cement concrete pavements (3). This research utilized a Wirtgen 1900C mill modified by adding additional teeth. There were 411 teeth at a 5 millimeter transverse spacing on a 6 ft. 4 in. long drum. About 0.5 in. of the surface was removed with a drum speed of 100 rpm and forward speed of 30 ft. per minute. This research found that the milling operation provides an acceptable surface texture with improved Friction Number when compared to a non milled surface.

1.2.2 Wisconsin Department of Transportation (WisDOT)

In 1999, WisDOT used light texturing with fine milling drum to remove the ruts on the pavement, which pose danger to traffic safety. A Wirtgen front-loading machine with 12.5 ft drum was used. It has 3 times the teeth of a conventional drum (15). The rutting was insignificant for first two years after milling. The ruts became significant from the third year. The pavement distress index values were slightly decreased after the road was fine milled. The results lasted for less than a year. There was no significant change in IRI values before and after milling. However, there was significant change in interior noise level before and after milling. But this difference disappeared three months after milling.

Table 1. Summary of Light 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	1985	Wirtgen 1900C	0.5 in	17-28 ft/m	411	6 ft 4 in	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	2010	Roadtec RX900	0.5 in	N.A	840	12.5 ft	N.A	N.A.	Smooth surface	N.A	N.A	N.A
Georgia Department of Transportation	2009	N.A	1/16 in	20 ft/m	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	2006-2012	Wirtgen 130F	less than 0.3 in	N.A	300	1300 mm (4.27 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	2011	N.A	0.375 in - 0.5 in	N.A	700-1000	12.5 ft	N.A	N.A.	N.A.	N.A.	N.A.	N.A.
Wisconsin Department of Transportation	1999	Wirtgen	N.A	25 ft/m	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	2004	Wirtgen W2000	0.3 in - 0.5 in	N.A	672	N.A	AC	N.A	N.A	N.A.	Improve driving comfort by minimizing ruts	N.A
Israel	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

1.2.3 Georgia Department of Transportation (GDOT)

GDOT used texture and friction measurements to develop parameters and criteria to evaluate the quality of micro milling prior to rehabilitation of porous friction courses in Georgia. In this project, a 12.5 ft. drum with approximately 500 teeth was used. This was not a light texturing project, but the results show that by keeping the milling speed at 20ft/min the surface texture depths of 1.6-3.2 mm can be achieved (9).

1.2.4 Tennessee Department of Transportation

In the summer of 2011, a Tennessee contractor conducted a light texturing over a 5.5-mile stretch of S.R. 96 in Dixon County. The milling cut 5/8 inch deep at most and averaged between 3/8 and a 0.5 deep (16).

1.2.5 Nebraska Department of Transportation

Nebraska is using fine milling to rectify shallow ruts on the pavement. They are not going to replace milled surface with asphalt if the pavement is in good condition. The micro milling is carried out by roadtec RX900. The milling drum is 12 ft. 6 inch wide. There are 840 teeth on the drum. The maximum milling depth was 0.5 inch. It was observed that that profiling takes out ruts but does not tear up the surface (17).

1.2.6 New Zealand

In 2006, 2010 and 2012, Higgins performed fine milling operations on three projects in New Zealand (18). It was reported that the cost of fine milling process is approximately 10-20% of the cost if resurfacing is performed. After the milling, the road is immediately cleaned, marked and reopened to traffic. In those projects, Wirtgen 130F Profiler was used and the drum width is 1300 mm. Figure 7 shows the pavement surface before and after the milling.

Figure 7. New Zealand Fine Milling Project: Before and After the Fine Milling

1.2.7 Israel

Since 2001, light texturing method was used in Israel to address problems of skidding accidents and normal problems such as loss of macrotexture, polishing, bleeding etc. Usually the depth of milling is limited to 1 cm (0.4 inch). The durability of light texturing method is largest compared to all other methods since the texture depth is large. Rougher texture is obtained by light texturing when compared to other methods. Travelling on textured pavements is noise and less convenient. The use of this method is limited to high sloped roads or roads that have tight radii. This method is suitable to use in mountainous areas where there is speed restriction (1).

1.2.8 Germany

In 2004, light texturing was used to rectify the defects such as ruts and frost damage in Germany. Wirtgen W2000 milling machine was used to remove the asphalt pavement to a depth of 0.8 cm (0.3 inch) to 1.2 cm (0.5 inch). The milled section was simultaneously cleaned by vacuum sweepers so that the first layer of mix could be laid with optimum adhesion. Drums of this type are equipped with 672 point attach tools and produce a profile with correspondingly good grip. Fine milling also eliminated cross sectional convexity. The results showed that fine milling itself is sufficient to improve the driving comfort by minimizing the ruts on the pavement (19).

1.3 Skid Resistance

Skid resistance of pavements is the friction force developed at the tire-pavement contact area. This force is an essential component of traffic safety because it provides the grip that a tire needs to maintain vehicle control and for stopping in emergency situations. Skid resistance has two major components: adhesion and hysteresis (11). Adhesion results from the shearing of molecular bonds formed when the tire rubber is pressed into close contact with pavement surface particles. Hysteresis results from energy dissipation when the tire rubber is deformed when passing across the asperities of a rough surface pavement. These two components of skid resistance are related to the two key properties of asphaltic pavement surfaces: microtexture and macrotexture (Figure 8).

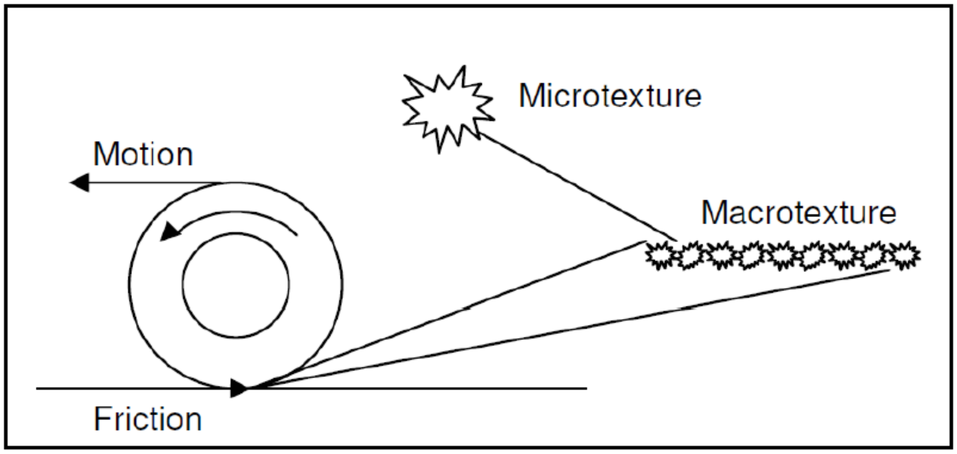


Figure 8. Friction Force and Its Components (20)

Microtexture refers to irregularities in the surfaces of the stone particles (fine-scale texture) that affect adhesion. These irregularities are what make the stone particles feel smooth or harsh to the touch. The magnitude of microtexture depends on initial roughness on the aggregate surface and the ability of the aggregate to retain this roughness against the polishing action of traffic. Accordingly, microtexture is an aggregate-related property that can be controlled through the selection of aggregates with desirable polish-resistant characteristics. Microtexture and adhesion contributes to skid resistance at all speeds and are the prevailing influence at speeds less than 30 mph (11).

Macrotexture refers to the larger irregularities in the road surface (coarse-scale texture) that affects hysteresis. These larger irregularities are associated with voids between stone particles. The magnitude of this component will depend on several factors. The initial macrotexture on a pavement surface will be determined by the size, shape, and gradation of coarse aggregates used in pavement construction, as well as the particular construction techniques used in the placement of the pavement surface layer. Macrotexture is also essential in providing escape channels to water in the tire-surface interaction, thus reducing hydroplaning. Macrotexture and hysteresis are less important at low speeds but a coarse macrotexture is very desirable for safe, wet-weather travel as the speed increases. Macrotexture is considered the primary factor in skid resistance at speeds over 40 mph (65 kph) (21).

1.3.1 Skid Resistance Measurement

Field skid resistance is generally measured by the force generated when a locked tire slides along a pavement surface. State-of-the-art friction testing comprises of applying a standard tire to pavement surfaces with controlled wheel slip (0 to 100 percent slip) while measuring friction between a tire (on the wheel) and pavement. There are four main types of skid resistance measuring approaches (22):

- locked wheel, where the force is measured while a 100 percent slip condition is produced;
- sideway force, where the force is measured on a rotating wheel with a yaw angle of 20°;
- fixed slip, where friction is measured for wheels that are constantly slipping; and
- variable slip, where devices are designed to measure at any desired slip, sweep through a predetermined set of values, or seek the maximum friction.

The numerical skid resistance value associated with a specific pavement is usually presented as a two-digit constant, determined by multiplying the measured friction coefficient by 100. This number is described as the friction number (FN) or skid number (SN). SN is usually followed by the speed value at which the friction measurement was taken and the type of tire. Representative values for skid numbers obtained with a skid trailer, and the associated recommendations for each value, are depicted in Table 2 (20). Table 3 presents a list of devices that can be used to measure the pavement skid resistance.

Table 2. Typical Skid Resistance Value Ranges

Skid Number	Recommendations
30	Take measures to correct
30	Acceptable for low volume roads
31-34	Monitor pavement frequently
35	Acceptable for heavily traveled roads

Table 3. List of Skid Resistance Measurement Devices

Device	Slip Speed	Need Traffic Control	Test Procedure
Friction Trailer	50 mph	No	ASTM E-274
British Pendulum Tester	6 mph	Yes	ASTM E-303
Dynamic Friction Tester	0-55 mph	Yes	ASTM E-1911

Friction Trailer

The trailer is towed at a constant speed over the tested pavement when used to measure the skid resistance. When the test is initiated, water is sprayed ahead of the tire so the wet pavement friction can be tested. The wheel is fully locked, and the resulting torque is recorded. Based on the measured torque (converted to a horizontal force) and dynamic vertical load on the test wheel, the wet coefficient of friction between the test tire and pavement surface is calculated. The skid number (SN) is then reported as the coefficient of friction multiplied by 100. The same speed should be maintained before the test and when the wheel is locked. The friction trailer is typically equipped with two types of tires: a rib tire on the right side according to American Society for Testing and Materials (ASTM) E501 and a smooth tire on the left side according to ASTM E524. Following the recommendation of the ASTM E274 specification, the test speed (30, 40 or 50 mph) and type of tire (R for rib tire and S for smooth tire) should be cited when the skid number is reported. For example, SN40S indicates that the test was performed at a speed of 40 mph with the smooth type of tire. The friction trailer used by TxDOT is equipped with smooth tires and travels at a speed of 50 mph.

British Pendulum Tester

The British pendulum tester (Figure 9), BPT, is a dynamic pendulum impact-type device for measuring surface friction. It measures the energy loss when a rubber slider edge is propelled over a test surface. The tester is equipped with a standard rubber slider. During testing, the pendulum is raised to the locked point with a height that is adjusted so that the rubber slider just comes in contact with the pavement surface. When the pendulum is released and reaches the test surface, its potential energy becomes its maximum kinetic energy. As the rubber slider slides over the test surface, the friction reduces the kinetic energy of the pendulum in proportion to the level of friction. When the slider leaves the test surface, the reduced kinetic is converted to potential energy as the pendulum swings to its maximum height. The difference between the height before the release and the recovered height is equal to the loss of the kinetic energy due to the friction.

The test method is covered in ASTM E-303. The test result is reported as the British Pendulum Number (BPN). BPN is measured directly using a drag pointer. The greater the friction between the rubber slider and the test surface, the greater the BPN. The average slip speed decreases as the friction increases because the average velocity of the slider relative to the test surface is a function of the friction. Usually, the typical slip speed is assumed to be 6 mph (10 km/h) for the BPT. BPT is fitted with a scale that measures the recovered height in terms of the BPN over a range of 0 to 140. BPN mainly depends on the microtexture because the slip speed is very low. The British Pendulum Number (BPN) is approximately 100 times the coefficient of friction (23).

Figure 9. British Pendulum Tester

Dynamic Friction Tester

The dynamic friction tester (Figure 10), DFT, is a portable device for measuring friction. The test procedures are covered in ASTM E-1911. The fundamental principle is the Coulomb's friction law. This device consists of a horizontal spinning disk fitted with three spring-mounted rubber sliders. During testing, the disk is lowered so that the three sliders are in contact with the test surface under a constant force perpendicular to the test surface. The disk is driven by a motor and rotates at a tangential speed varying from 0 to 50 mph, which is determined from the rotary speed of the disk. Water is delivered to the test surface by a water supply unit. The horizontal force required to overcome the friction is measured by a transducer. The test result is reported as the coefficient of friction and is plotted against the speed. Like the British pendulum tester, use of the DFT in field pavement friction tests requires traffic control.

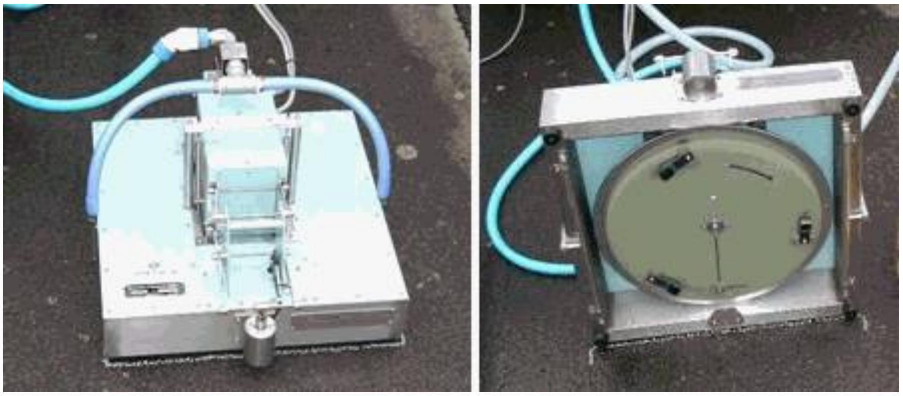


Figure 10. Dynamic Friction Tester

1.3.2 Macrotexture Measurement

Sand Patch test

The macrotexture can be evaluated using sand patch test method (Figure 11) by measuring the Mean Texture Depth (MTD) as per ASTM E-965 procedure. According to a research conducted by Virginia DOT (14), macrotexture depth as measured by the sand patch method showed a higher correlation with skid number (SN40S) than any other factor investigated. The test involves spreading a known volume of uniformly rounded glass beads (or sand) on a clean pavement surface and measuring the area covered. The material spread on the surface fills the surface voids completely up to the tips of surface aggregates. Hence, the average texture depth from the bottom of the surface voids to the top of the aggregates can be calculated by measuring the area.

$$\text{Mean Texture Depth (MTD)} = 4V/\pi D^2$$

where:
V = sampling volume, in^3
D= Average diameter of the area covered by the material, in.

Figure 11. Sand Patch Test

Circular Texture Meter (CTM)

Circular Texture (CT) Meter is a laser based device for measuring surface texture of pavements and it is described in ASTM E2157. CT meter has a Charged Couple Device (CCD) laser displacement sensor which is mounted at a height of 80mm 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 142mm. The CT meter uses the laser to measure the profile along the periphery of the circle (with 142mm radius). The laser sensor takes 1024 samples in one round at 0.87 mm interval along the periphery of the circle. The data collected is converted into digital format and stored in the memory of a laptop. To calculate the Mean Profile Depth (MPD), the data along the complete circle is divided into eight equal arcs each of 111.5 mm length. The calculated MPD for each segment is averaged and presented as MPD for the test surface. Figure 12 shows a CT meter device.

$$MTD = 0.79MPD + 0.23$$

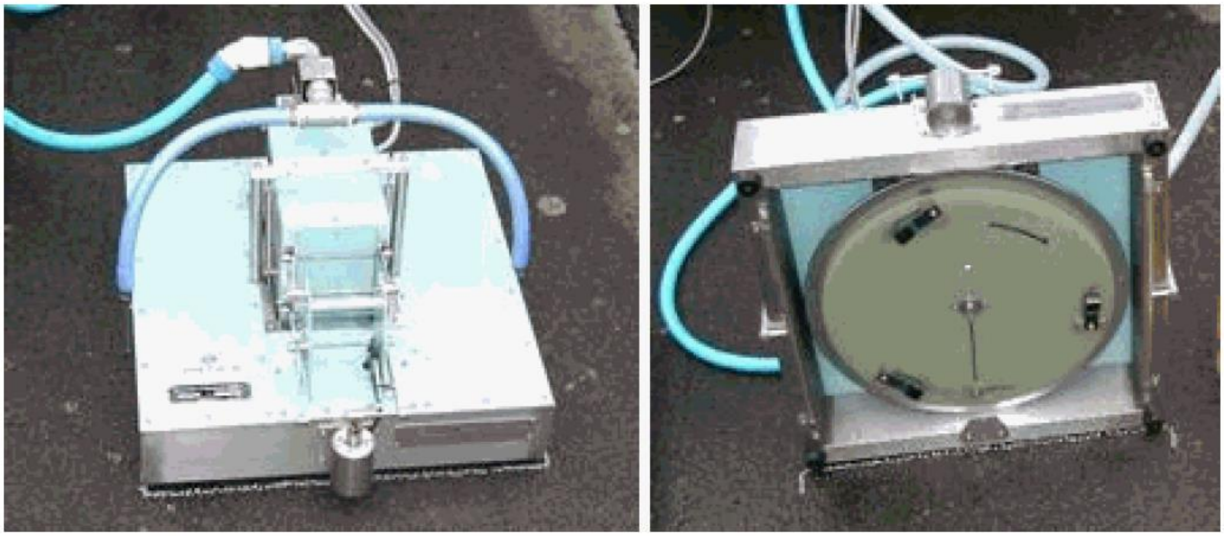


Figure 12. Circular Texture (CT) meter

Laser Texture Scanner

The Laser Texture Scanner (Figure 13) is designed to scan and precisely measure the texture content of any surface. Once a scan has been completed, the scanner immediately calculates and displays the following indices on the sunlight readable LCD display:

- Mean Profile Depth (MPD)
- Texture Profile Index (TPI)
- Estimated Texture Depth (ETD)
- Band pass selectable
- Elevation variance
- Slope variance

The scanner is lightweight, portable and is powered using high cycle rechargeable batteries that can provide up to one hundred scans per charge.

Figure 13. Laser Texture Scanner

Microtexture measurement

Currently there is no system capable of measuring microtexture profiles at highway speeds. Because of the difficulty in measuring microtexture profiles, a surrogate for measuring microtexture is generally preferred. It was found that the British Pendulum Numbers (BPN) were highly correlated with the parameter. Therefore, the BPN values could be considered as the surrogate for microtexture (20).

1.3.3 Texture and Friction Number

Friction Number (FN) can be predicted by using microtexture and macrotexture. The relationships are measured based on macrotexture measured using SPM and microtexture on BPN (11).

$$FN40R = -44.74 + 2.29BPN - 25.48MTD$$
$$FN40S = -48.21 + 1.89BPN + 264.6MTD$$

Where,
BPN = British pendulum number.
FN40R = Friction number using ribbed tire at 40 mi/hr.
FN40S = Friction number using smooth tire at 40 mi/hr.
MTD = Mean texture depth, in.

A power law relationship exists between the macrotexture and the skid number at 65 kph (40 mph). This relationship is also affected by the microtexture as measured using the British Pendulum Test (Figure 14).

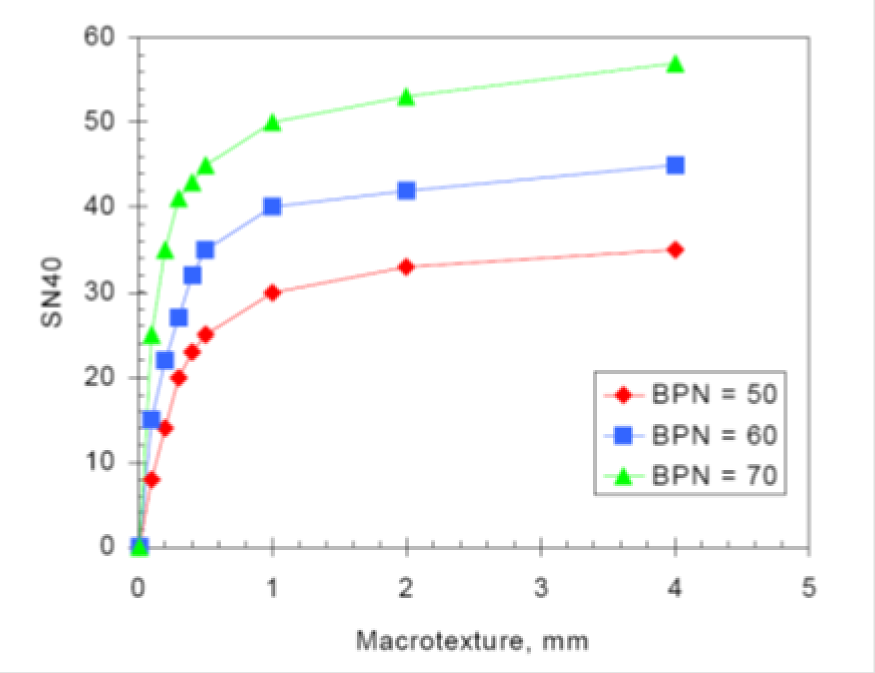


Figure 14. Effect of micro- and macrotexture on skid resistance (21)

Chapter 2. Survey

Research project advisor Karl Bednarz and John Bohuslav helped the research team conduct a survey seeking feedback from each district. The survey addressed the following three questions:

1. Does your district have a milling machine?
2. If so, does your district have any roadways sections (1000 ft min) you plan to texture in the next 4 months that will not receive a new surface (sealcoat, overlay, etc) for at least a year after milling?
3. If you answered yes to both #1 and #2, who would be a good point of contact in your district to possibly study these sections?

The survey result was made available to the research team for further exploration. A total of 22 feedbacks were collected in October 2012. The feedback information from this survey is presented below in Table 4. Among all 22 surveyed districts, 18 have milling machines. 3 districts (San Angelo, San Antonio and Yoakum) were planning to texture between October and December of 2012. The research team contacted those 3 districts and collected the pre- and post-milling skid data from test sites in San Angelo and San Antonio. The research team also collected the post-milling skid data from Yoakum district. 10 districts (Beaumont, Brownwood, Bryan, Laredo, Lubbock, Pharr, San Angelo, San Antonio, Tyler and Yoakum) indicated that they might have texturing projects next year. The research team is following up with those districts to set up more test sections.

The research team also developed an online survey consisting of 18 questions (see attached Appendix). This survey was designed to identify the best practice of using the light-texturing method in Texas. It was prepared to be submitted to TxDOT districts who have done light texturing before. The survey provides a brief overview of this research project and queries the districts regarding the use and application of light-texturing, the equipment and configurations used, pavements milled. The survey will collect information such as milling machine and drum configuration used, milling specifications, speed of milling machines, project related information such as rehabilitation actions, pavement type, project location and duration, and the effect on skid resistance.

Table 4. Survey Conducted on 10/15/2012

District	Representative	Response #1	Response #2	Response #3	Comments
Abilene	Brian Crawford	Yes	No	NA	
Amarillo	Mike Taylor	Yes	No	NA	
Atlanta	Lance Simmons	Yes	No	NA	
Beaumont	Duane Browning	No	No	Duane Browning	The Beaumont District does not have a milling machine. We do have a purchase of service for a milling machine. We have used the milling machine on at least one occasion to improve the skid on a roadway. I am unaware of any problem areas that we would address in this manner at this time.
Brownwood	Carl Johnson	No	Yes	Carl Johnson	Another thought, I did a little research on milling machines a few years ago and since then have been specifying different drums to handle different things I was trying to do (mostly bridge deck issues). Along those lines, I would prefer to use a finer tooth drum to do roadway milling for skid. I would be very interested in the results of skid numbers after milling with different drums.
Bryan	Terry Paholek	Yes	Yes	Terry Paholek	We just did one section and at this time we have nothing on our list. But we are reviewing the WWARP list and may have something to add to our milling list in the near future. Yes we have a milling machine and we use it to improve skid scores, but usually the texturing occurs quickly after a need is found.
Childress	Darwin Lankford	Yes	No	NA	CHS has a milling machine but I'm not aware of any roads to be milled & left that way for a year or more. We're fixing to overlay a road that's been that for just over a year, but that's it.
Corpus Christi	Victor Pinon	Yes	No	NA	We do have a milling machine, but we do not know what roads will be textured only and left in that condition for a year. I do know that our machine has about 354 teeth and is used more for fine texturing and milling 2-3 inches. We have milled several connecting ramps (SH 358 and SH 286) at IH 37 in Corpus Christi to improve skid and reduce wet weather accidents. Those areas have been down for about a year. However, we have plans to place new hot mix over those areas.
Dallas	Ron Johnston	Yes	No	Chris Johnson	We currently have no plans to do this but have in the past. These areas are now covered up. Chris Johnson , Maintenance Supervisor in Kaufman/Rockwall counties has be doing most of this in the district.
Houston	Jim Hunt	Yes	No	NA	The Houston District has a milling machine. However the answer to question number 2 is “NO” We have no plans on milling, and leaving the milled surface exposed to traffic for any long period of time.
Laredo	David Salazar	Yes	Yes	David Salazar	We have a milling machine that we have used on occasion to for light texturing, unfortunately the ones that come to mind will be overlayed shortly with hotmix.
Lubbock	Ted Moore	Yes	Yes	Ted Moore or David Barrera	We have a milling machine, but I am not aware of any sections we are planning to leave with the textured surface. I’ll do some more checking though, and see if David is aware of any.
Lufkin	Paul Montgomery	NA	No	NA	We have no areas that are not sealed over.
Odessa	Mike Stroope	Yes	No	NA	ODA has a milling machine but no plans to texture anything
Paris	Mykal Woodruff	No	No	NA	
Pharr	Rex Costley	Yes	Yes	Rex Costley or Carlos Solis	Pharr District contains a milling machine. Point of contact is Carlos Solis and myself. We are gearing up for the upcoming SC season but we should have some stretches of pavement that might serve your need near the timeframe you are looking at.
San Angelo	Karl Bednarz	Yes	Yes	Karl Bednarz	We do have a milling machine and have identified some areas to use in this study. John Bohuslav in SAT has some also.
San Antonio	John Bohuslav	Yes	Yes	John Bohuslav	See below for area of freeway with high traffic that we plan to texture in winter. SH 151 kind of runs West and East.
Tyler	Michael Schneider	Yes	Yes	Michael Schneider or Randy Ralson	We use the mill machine for texture on occasion, but do not have any planned at this time. The last we did was last year, Sept. or Oct., were we removed seal coat that had shoved at intersections.
Waco	Tony Moran	Yes	No	NA	
Wichita Falls	Tim Hertel	Yes	No	NA	
Yoakum	Randy Zimmerman	Yes	Yes	Andy Brzozowski	

Chapter 3. Experimental Design

3.1 Scope

The project progress meeting on January 3, 2013 outlined and discussed the testing and experimental work done towards establishing an experimental design program for the project. Prior to the meeting, the research team had tested, analyzed and evaluated 3 different test sites in the San Antonio, San Angelo and Yoakum districts. A defunct TxDOT rest area on IH 35 between New Braunfels and San Antonio was used to evaluate the effect of milling machine speed, drum speed and depth of cut on the milling texture produced on a hot-mix asphalt (HMA) surface layer. Similarly, milling was done on a flushed seal coat layer on US 87 outside Sterling City in San Angelo. For these sections, texture and friction testing was done both prior to and after milling of the test sections. A milled seal coat section on FM 512 outside Bay city in Yoakum was also tested. Milling on this section was done to address roughness issues and as such falls outside the scope of the study, which is focused on milling done to address low skid. It was evident from an evaluation of the data collected on the section in Yoakum that, in the context of this study, little or no benefit is gained from testing sections which are milled to address roughness issues. The research will therefore only focus on projects that are milled to specifically address skid issues. Another important criterion for the selection of test sections is that they remain open and uncovered for at least 1 year following milling. The study aims to follow-up with texture and friction measurements after milling at 3, 6, 12 and 18 month intervals to investigate the influence of the milling parameters on the friction longevity.

3.2 Section Length

A critical aspect of the study that was brought to light by the testing to date is section length. Section lengths of 50 ft were initially used for the pre- and post-milling texture and friction tests but were found to be inadequate to effectively evaluate improvements in friction on the milled sections. This is related to the minimum section length over which the locked wheel skid tester can collect data. Following discussions with John Svab and John Wirth of TxDOT, a minimum test section length of 500 ft is recommended. Longer sections will provide additional friction data points. It is also recommended that skid data be collected in turbo-skid mode to provide additional data.

3.3 Milling Speed

Milling speeds ranging from 10 feet per minute (fpm) through 120 fpm have been evaluated to date. From a survey of the districts, the speed at which light-texturing is typically applied ranges between 70 - 80 fpm. An evaluation of the data collected on the sections in the San Antonio and San Angelo districts indicates that friction tends to increase with milling speed. At very high milling speeds i.e. above 100 fpm, a very rough surface texture is 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. Low milling speeds i.e. below 50 fpm are used in light-texturing applications to provide a smoother surface and to address roughness issues. At these low speeds, the teeth on the drum may make repeated or overlapping cuts in the same groove producing a lower macro-texture. 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 indicates that for a standard milling drum, a speed above 50 fpm is required to prevent overlapping cuts. For practical purposes, therefore, it is recommended that milling speeds between 60 and 100 fpm be evaluated as part of this study.

3.4 Depth of Cut

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. Depths of cut in the order of 0.25 inches are used when texturing seal coats since larger cuts may result in tearing and raveling of the surface treatment with chunks of the surface being ripped from the surface in the process. Larger depths of cut may be applied to address surface rutting if evident. Given the surface height variations typically found on both HMA and in particular seal coat surfaces, this parameter cannot be controlled very accurately. For the purpose of this study it is recommended, therefore, that the research evaluate two depths of cut i.e. 0.25 and 0.5 inches, taking into account the district's decision and preference.

3.5 Milling Drum

Two types of milling drums are used for light-texturing in Texas. 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 San Antonio district uses this type of drum on their Wirtgen milling machine. The San Angelo district has the Bitelli machine that uses a fine milling drum with about 300 teeth that cut grooves about 5/16 of an inch apart. Both machines operate at a drum rotational or angular velocity of about 96 rpm. The Wirtgen milling machine is able to vary the drum's angular velocity at three settings i.e. low (60 rpm), medium (80 rpm) and high (100 rpm), although the machine is typically operated in the high speed mode. Computer simulations were run to investigate the influence of the drum's rotational speed on milling pattern. Figures 15, 16 and 17 show the resulting patterns for drum speeds of 60, 80 and 100 rpm for a standard milling drum operated at a milling speed of 80 fpm. From these figures 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 may not be possible to vary the drum speeds on the different milling machines used for this study it is recommended that all milling be done with the drum speed set to 100 rpm.

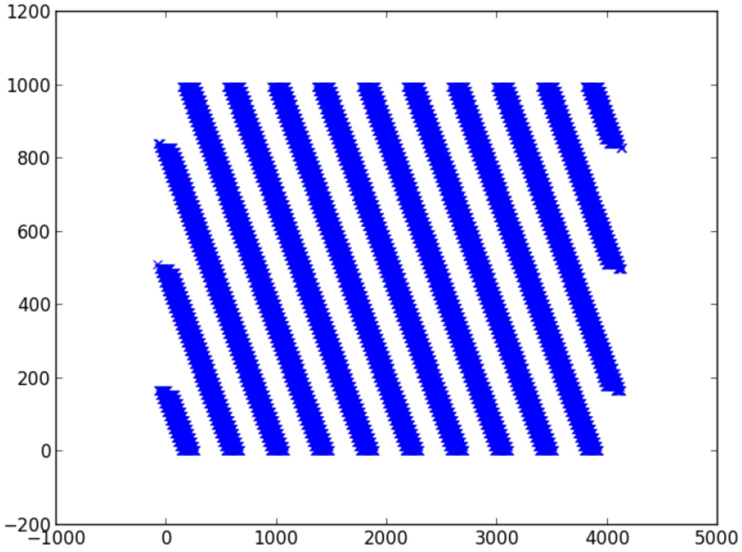


Figure 15. Milling pattern at a drum speed of 60 rpm

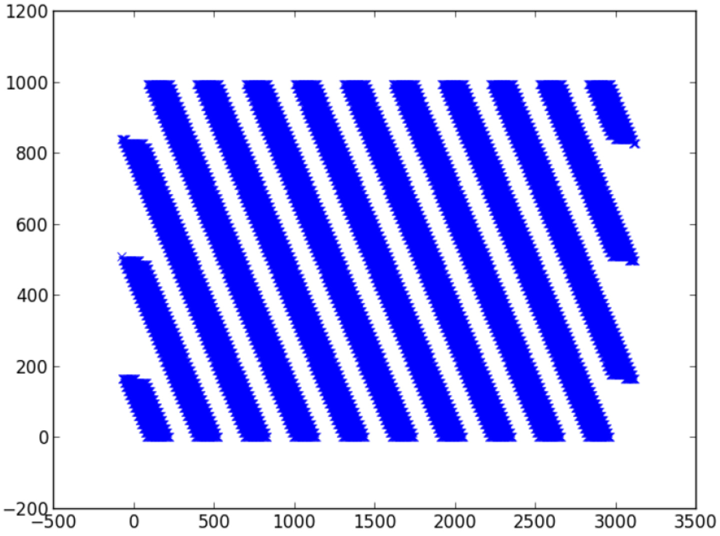


Figure 16. Milling pattern at a drum speed of 80 rpm

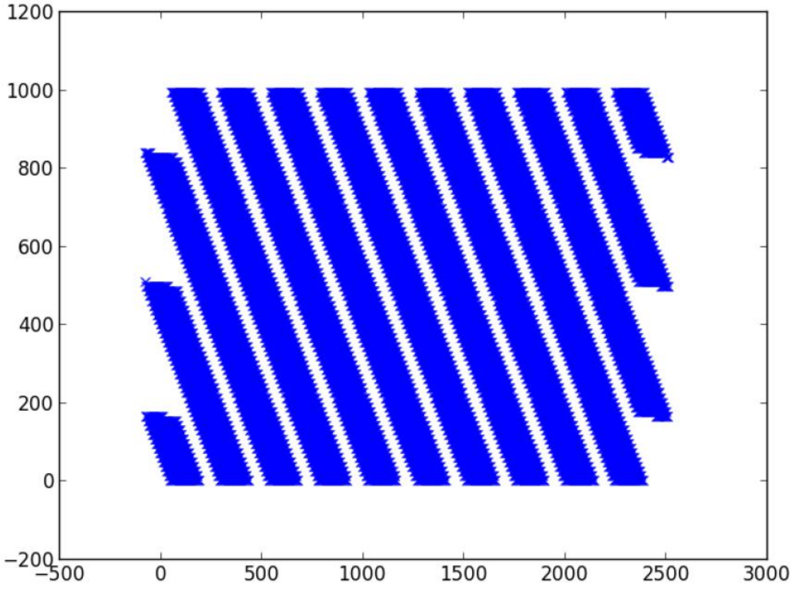


Figure 17. Milling pattern at a drum speed of 100 rpm

3.6 Testing

Testing for this project entails macro-texture and friction tests done prior to and after milling with subsequent measurements at 3, 6, 12 and 18 month intervals. For the sections tested to date, the macro-texture of the surfaces was measured using both the sand-patch method and the circular texture meter (CTM). A strong correlation is evident between the sand patch and CTM measurements. For this reason it is recommended that future macro-texture testing on the project be done using only the CTM, which will reduce the variability of macro-texture measurements, particularly for rougher surfaces. Since a dynamic friction tester (DFT) was not available for the study, the researchers made use of a British Pendulum Tester (BPT) to evaluate surface friction prior to and after milling. The BPT effectively measures friction over a 5 inch distance at a speed of about 6 mph. It was found to be very variable and generally insensitive to changes in the milling parameters. Further use of the BPT is not recommended for this study; instead friction data collected using the TxDOT locked wheel tester over the longer section lengths as discussed previously will provide the measures to assess the friction longevity of the milled surfaces. A DFT tester will be used if and when available to provide additional friction measurements. The test plan as originally proposed will be followed i.e. replicate testing in and between the wheel paths both prior to and after milling. Since longitudinal surface roughness in terms of International Roughness Index (IRI) is outside the scope and main focus of the study, future roughness testing is not recommended.

3.7 Test Sections

Based on responses from the study survey and discussions with District personnel, a limited number of sections will be available for the study. These sections have currently been identified: 1) Seal coat sections on US 87 in San Angelo, 2) HMA sections on Wurzbach Parkway in San Antonio, and 3) HMA sections on SH 151 in San Antonio, 4) Seal coat sections on US 277 in

Abilene, 5) HMA sections on I 10 in Tyler. The project is designed to cover both seal coat and HMA texturing projects (with hopefully varying aggregate types) in different climate zones throughout Texas.

Chapter 4. Field Testing

4.1 Test Section Selection

Various 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 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. Initially, Abilene, San Antonio, San Angelo, Tyler and Yoakum were identified as having desirable test sections and were considered for inclusion in the study. Sections in Yoakum were removed from consideration once it was determined that the milling plan was postponed by the District. While 15 sections have HMA surfaces, the other 16 sections have seal coat surfaces. The final 31 test sections used in the evaluation of milling operations are listed in Table 5, and are shown in Figure 18 to indicate the respective climatic zones.

Table 5. Pavement test sections selected for evaluation

Section ID	District	Highway	Milling Drum Type	Climatic Zone	Surface Type	Milling Machine Forward Speed (fpm)	Milling Depth (In)
1	San Angelo	US 87	Fine	dry & freeze	Seal Coat	30	0.2
2		US 87	Fine	dry & freeze	Seal Coat	50	0.2
3		US 87	Fine	dry & freeze	Seal Coat	70	0.2
4		US 87	Fine	dry & freeze	Seal Coat	80	0.2
5		US 87	Fine	dry & freeze	Seal Coat	30	0.5
6		US 87	Fine	dry & freeze	Seal Coat	50	0.5
7		US 87	Fine	dry & freeze	Seal Coat	70	0.5
8		US 87	Fine	dry & freeze	Seal Coat	80	0.5
9	San Antonio	Wurzbach Parkway	Standard	dry & non-freeze	HMA	60	0.5
10		Wurzbach Parkway	Standard	dry & non-freeze	HMA	70	0.5
11		Wurzbach Parkway	Standard	dry & non-freeze	HMA	80	0.5
12		Wurzbach Parkway	Standard	dry & non-freeze	HMA	90	0.5
13	San Antonio	SH151	Standard	dry & non-freeze	HMA	60	0.5
14		SH151	Standard	dry & non-freeze	HMA	70	0.5
15		SH151	Standard	dry & non-freeze	HMA	80	0.5
16		SH151	Standard	dry & non-freeze	HMA	60	0.5
17		SH151	Standard	dry & non-freeze	HMA	70	0.5
18		SH151	Standard	dry & non-freeze	HMA	80	0.5
19		SH151	Standard	dry & non-freeze	HMA	90	0.5
20	Abilene	US 277	Standard	dry & freeze	Seal Coat	50	0.5
21		US 277	Standard	dry & freeze	Seal Coat	60	0.5
22		US 277	Standard	dry & freeze	Seal Coat	80	0.5
23		US 277	Standard	dry & freeze	Seal Coat	100	0.5
24		US 277	Standard	dry & freeze	Seal Coat	50	0.5
25		US 277	Standard	dry & freeze	Seal Coat	60	0.5
26		US 277	Standard	dry & freeze	Seal Coat	80	0.5
27		US 277	Standard	dry & freeze	Seal Coat	100	0.5
28	Tyler	I20-W	Standard	wet & freeze	HMA	60	0.5
29		I20-W	Standard	wet & freeze	HMA	70	0.5
30		I20-W	Standard	wet & freeze	HMA	80	0.5
31		I20-W	Standard	wet & freeze	HMA	90	0.5

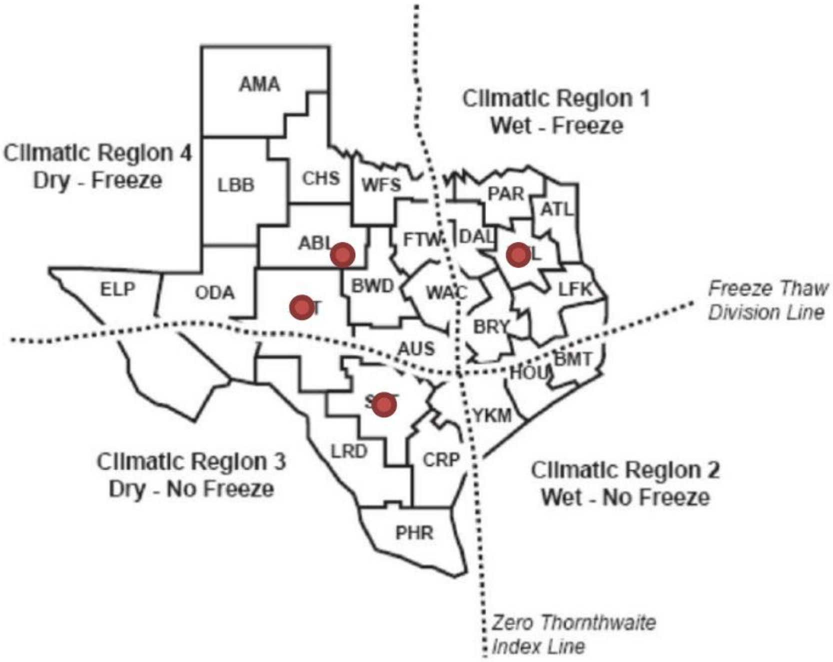


Figure 18. Location of test sections with respect to climatic regions

4.2 Collection of Pavement Data

The goal of the data collection effort was to develop a comprehensive database on the test sections to help in analyzing the optimal milling configuration and the relationships between friction and texture. The database was envisioned to include the following types of data:

- Surface Type: HAM or seal coat.
- Location
- Climate: dry-freeze, dry-nonfreeze, wetfreeze, 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).

4.3 Test Section Descriptions

The sections represent an array of asphalt pavement surface textures with different milling characteristics. The sections are mostly located on 4-lane highway facilities. The sections represent a range of traffic and climatic conditions.

4.4 Texture and Friction Testing of Test Sections

The following specific texture and friction (skid) tests (and their corresponding outputs) were planned for the selected test sections:

- Texture (macro-texture): CT Meter (ASTM E 2157) MPD.
    - CT Meter Macro-texture Measurements—Longitudinal and transverse macro-texture measurements were made in three locations in both the left and right wheelpaths 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 40 mi/hr.

4.5 Formal Testing

Milling and measurements were conducted during the December 2012 to August 2014 time period. Table 6 lists the specific dates of testing for each test section. Figure 19 illustrate the specific locations for texture measurements on the test sections. Figures 20 through 42 illustrate the resulting surface textures at different times of the research.

Table 6. Dates of texture and skid measurements

District	Section ID	Highway	Milling Date	Texture	Skid
San Angelo	1, 2, 3, 4, 5, 6, 7, 8	US 87	12/2/2012	12/2/2012 3/11/2013 7/22/2013 3/4/2014 8/7/2014	12/2/2012 4/4/2013 10/28/2013 2/4/2014 8/21/2014
San Antonio	9, 10, 11, 12	Wurzbach Parkway	1/15/2013	1/15/2013 5/7/2013 9/24/2013 2/13/2014 7/30/2014	1/15/2013 4/4/2013 7/3/2013 10/29/2013 1/22/2014 5/30/2014
San Antonio	13, 14, 15, 16, 17, 18, 19	SH151	2/25/2013	2/25/2013 7/22/2013 10/17/2013 2/4/2014 8/14/2014	2/25/2013 3/15/2013 9/5/2013 10/29/2013 1/23/2013 5/30/2013
Abilene	20, 21, 22, 23, 24, 25, 26, 27	US 277	4/23/2013	4/23/2013 9/4/2013 11/20/2013 3/18/2014	4/29/2013 8/29/2013 1/30/2014 5/4/2014
Tyler	28, 29, 30, 31	I20-W	12/3/2013	12/3/2013 2/20/2014	12/3/2013

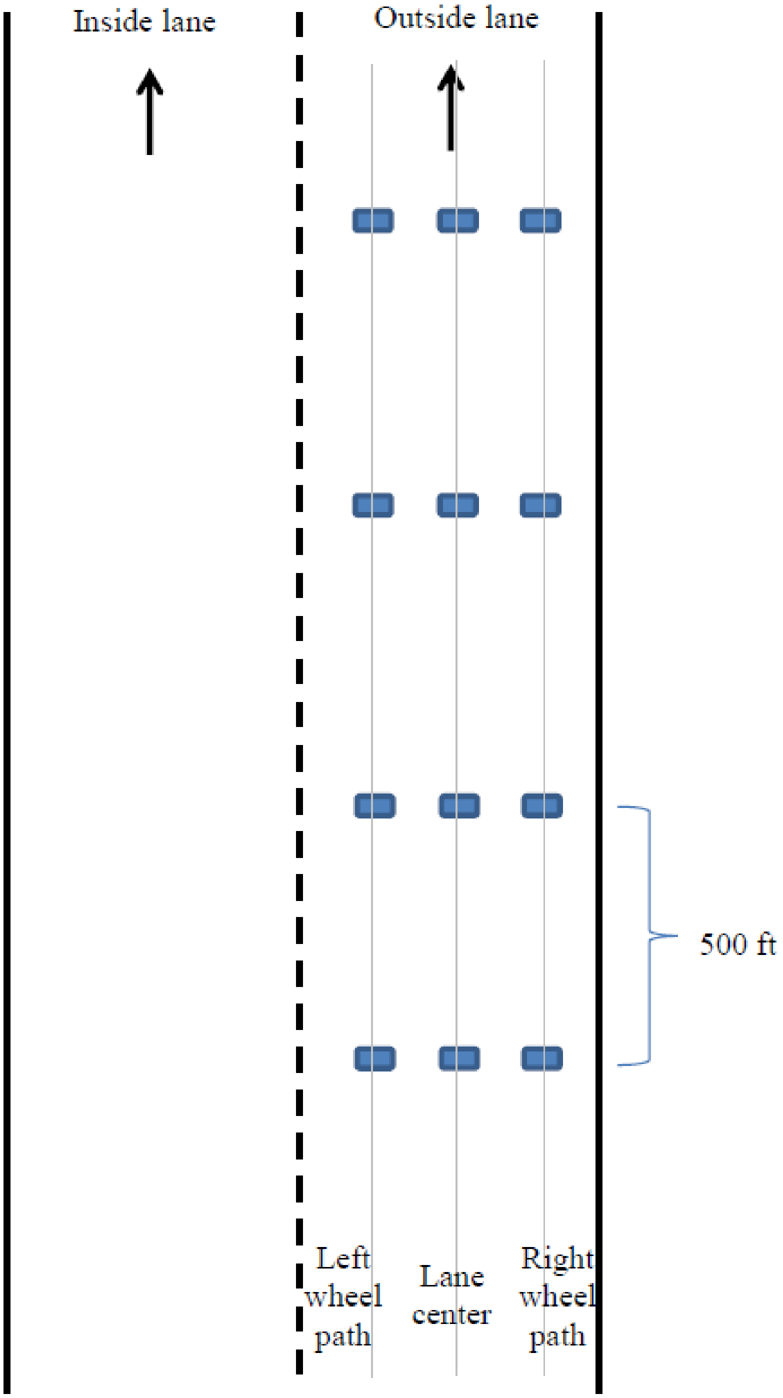


Figure 19. Location of standard texture measurements

4.5.1 US 87 (San Angelo) Test Site

Figure 20. Photos taken from US 87 test site before the milling

Figure 21. Photos taken from US 87 test site after the milling

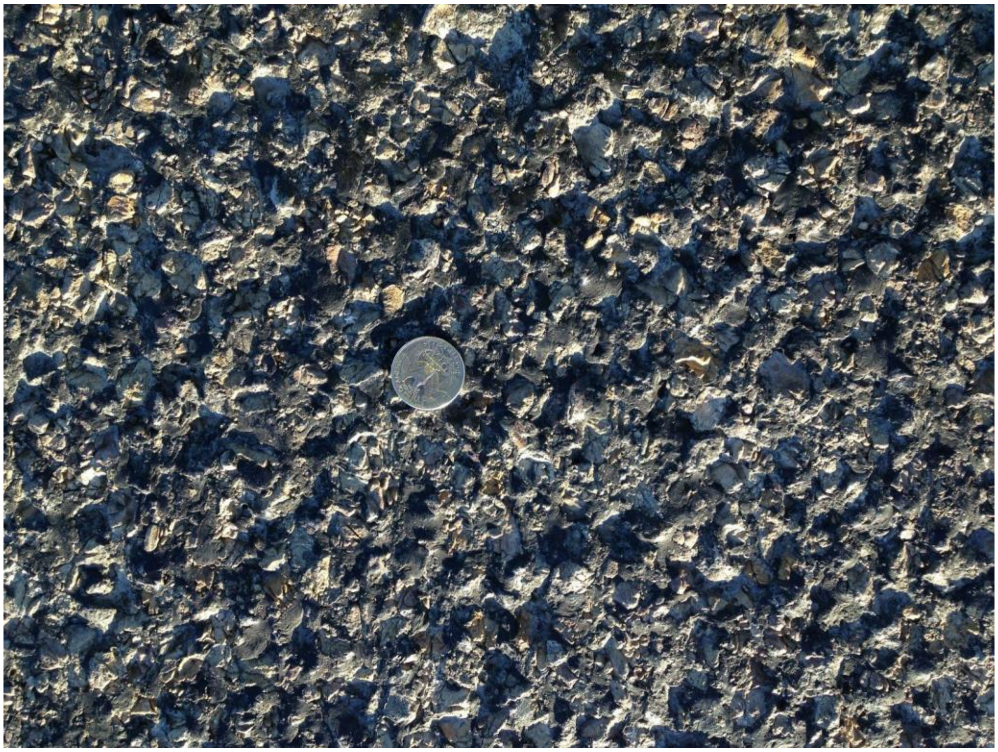


Figure 22. Photo taken from US 87 test site 3 months after the milling

Figure 23. Photo taken from US 87 test site 6 months after the milling

Figure 24. Photo taken from US 87 test site 12 months after the milling

Figure 25. Photo taken from US 87 test site 18 months after the milling

4.5.2 Wurzbach Parkway (San Antonio) Test Site

Figure 26. Photos taken from Wurzbach Parkway test site before the milling

Figure 27. Photo taken from Wurzbach Parkway test site after the milling

Figure 28. Photos taken from Wurzbach Parkway test site 3 months after the milling

Figure 29. Photos taken from Wurzbach Parkway test site 6 months after the milling

Figure 30. Photo taken from Wurzbach Parkway test site 12 months after the milling

Figure 31. Photo taken from Wurzbach Parkway test site 18 months after the milling

4.5.3 SH 151 (San Antonio) Test Site

Figure 32. Photos taken from SH 151 test site before the milling

Figure 33. Photos taken from SH 151 test site after the milling

Figure 34. Photos taken from SH 151 test site 3 months after the milling

Figure 35. Photo taken from SH 151 test site 6 months after the milling

Figure 36. Photo taken from SH 151 test site 12 months after the milling

Figure 37. Photo taken from SH 151 test site 18 months after the milling

4.5.4 US 277 (Abilene) Test Site

Figure 38. Photos taken from US 277 test site before the milling

Figure 39. Photos taken from US 277 test site after the milling

Figure 40. Photo taken from US 277 test site 3 months after the milling

Figure 41. Photo taken from US 277 test site 6 months after the milling

Figure 42. Photo taken from US 277 test site 12 months after the milling

Chapter 5. Data Analysis

A comprehensive statistical analysis of the field measurement is 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.

5.1 Texture and Friction Performance by Milling Machine Forwarding Speed

For this analysis, test sections were grouped into categories according to the milling machine forwarding speed. The results are presented in Figure 43 through 46, which shows the macro-texture and friction values at the end of the research period. Average Mean Profile Depth (MPD) and Skid Number (SN) values for all the sections constituting each speed category were plotted sequentially. Although many factors (e.g., climate, traffic, and pavement condition prior to the milling) influence the results shown in these figures, some general trends regarding the macro-texture and friction performance over time can be seen. Test sections with milling speed equal or higher than 70 feet per minute (fpm) showed the highest texture and friction levels. Test sections with HMA surface showed an increase in SN when the machine speed increases. However, this trend is not observed in the sections with seal coat surface.

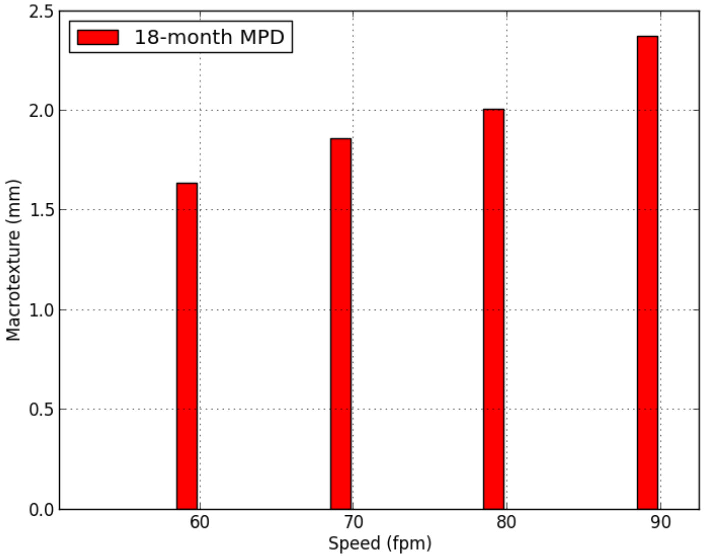


Figure 43. 18-month average MPD (HMA surface) of different forwarding speeds

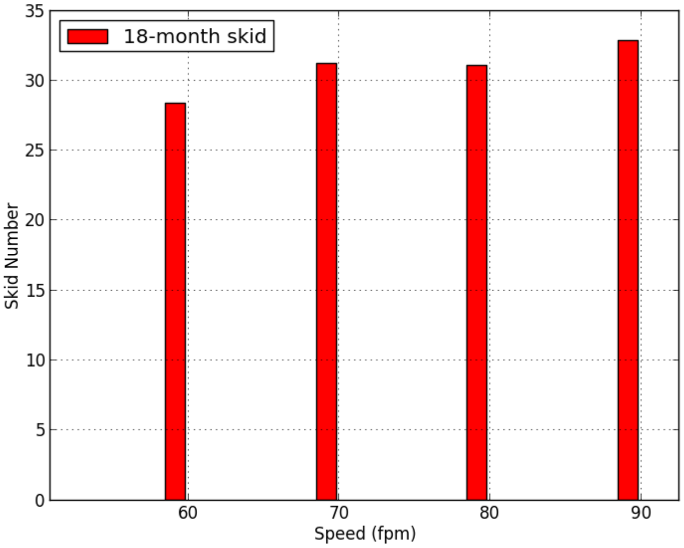


Figure 44. 18-month average skid number (HMA surface) of different forwarding speeds

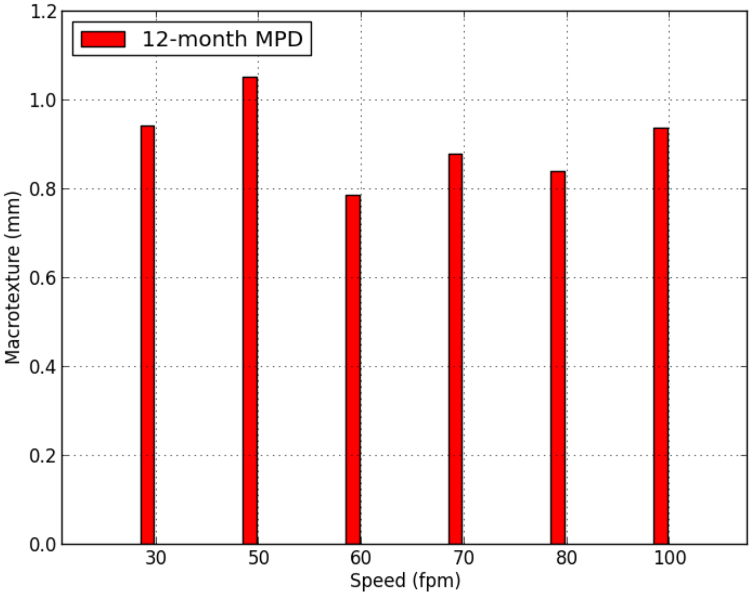


Figure 45. 12-month average macrotexture (seal coat surface) of different forwarding speeds

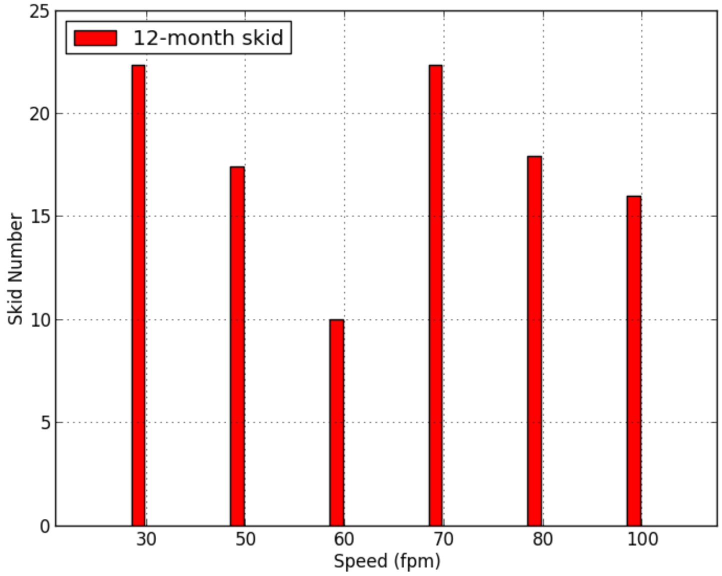


Figure 46. 18-month average skid number (seal coat surface) of different forwarding speeds

5.2 Durability Analysis

Figures 47 through 54 provide an indication of the durability of macro-texture and skid number for the different locations, forwarding speeds, cutting depths and surface types based on the texture and friction values obtained during the 18-month research period. These figures illustrate the reduction in texture depth and friction for each test location over time. As Figure 47 and 48 show, the sections with HMA surface exhibited higher level of texture depth and friction than the sections with 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 surface exhibited texture depth losses of 1.5 mm and skid number losses of 20 during the same time period. Because of the very limited number of test sections of each climate type and surface type, the effect of climate on texture and friction loss could not be determined. The data also illustrate the importance of using forwarding speed to maintain high levels of friction over time.

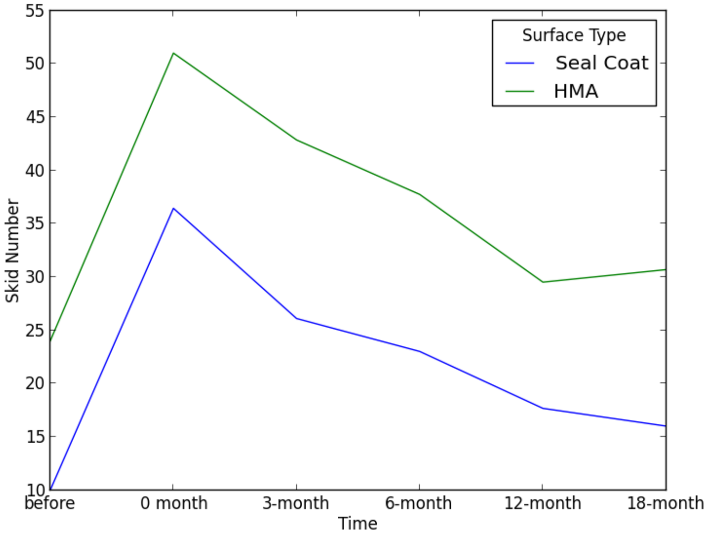


Figure 47. Skid number versus time for different surface types

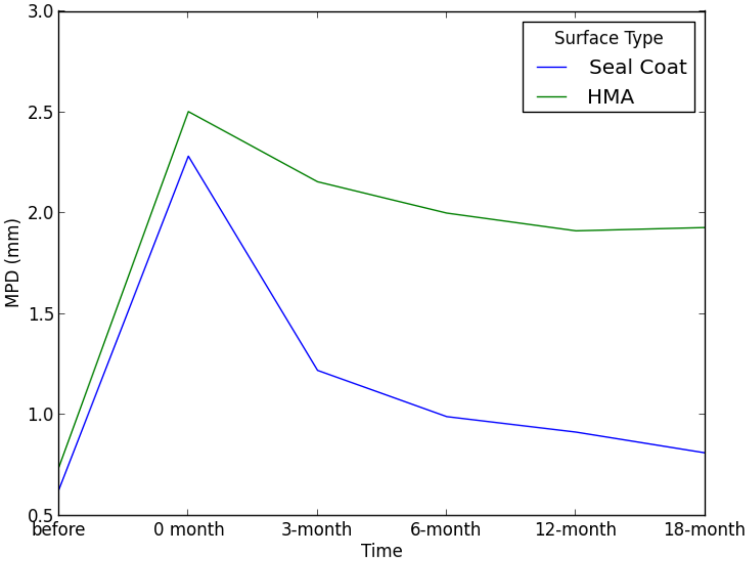


Figure 48. Macrotexture versus time for different surface types

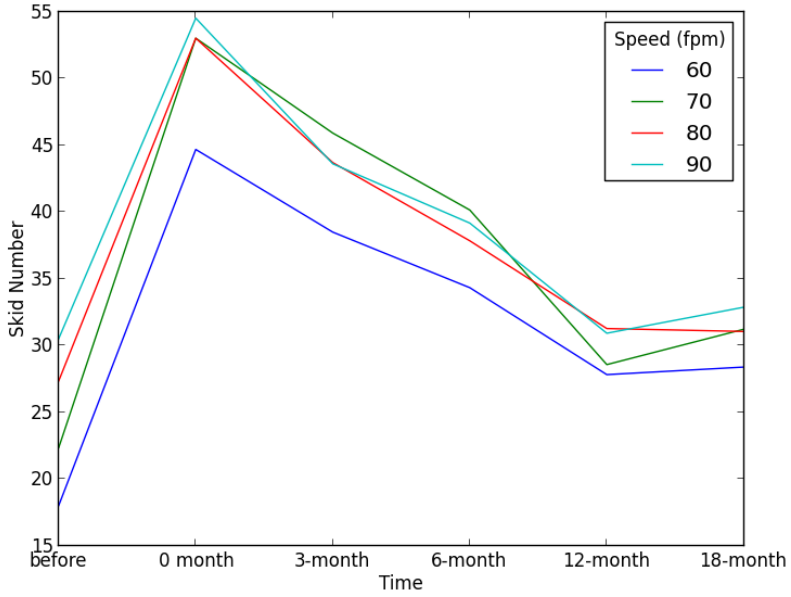


Figure 49. Skid number versus time for different forwarding speeds (HMA surface)

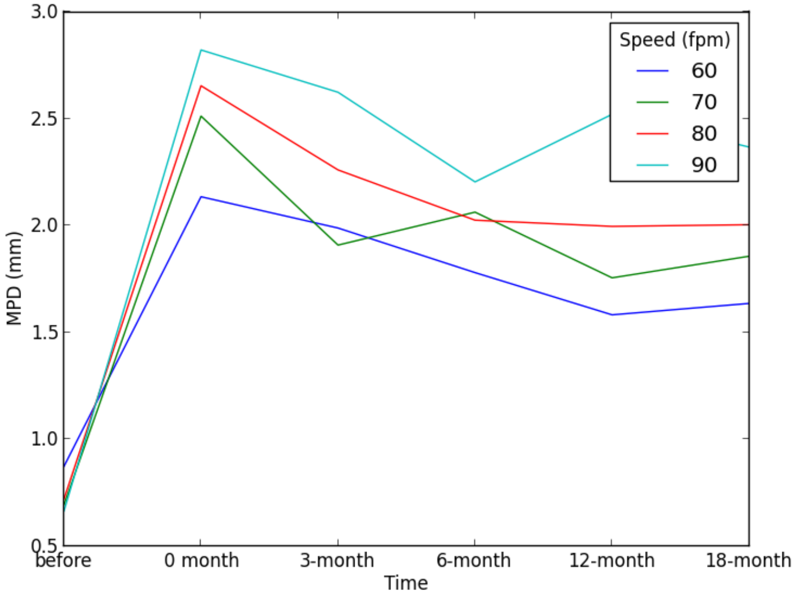


Figure 50. Macrotexture versus time for different forwarding speeds (HMA surface)

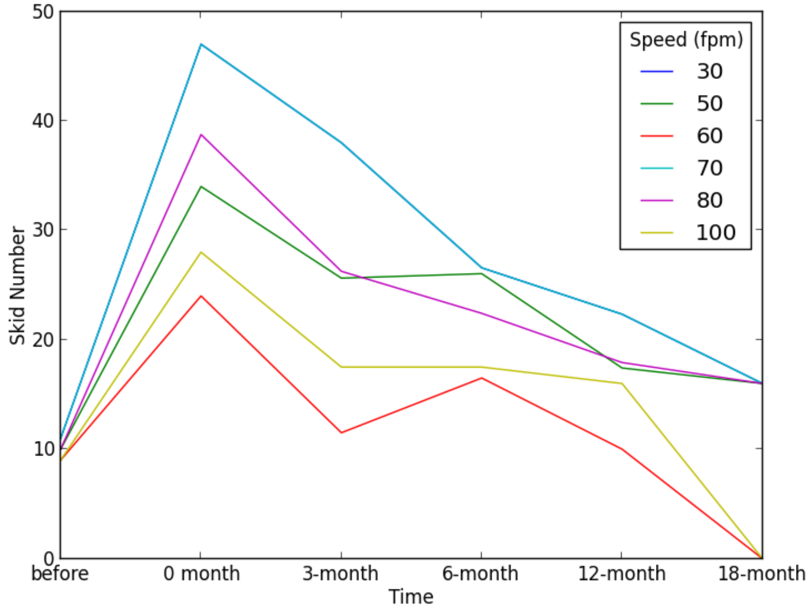


Figure 51. Skid number versus time for different forwarding speeds (seal coat surface)

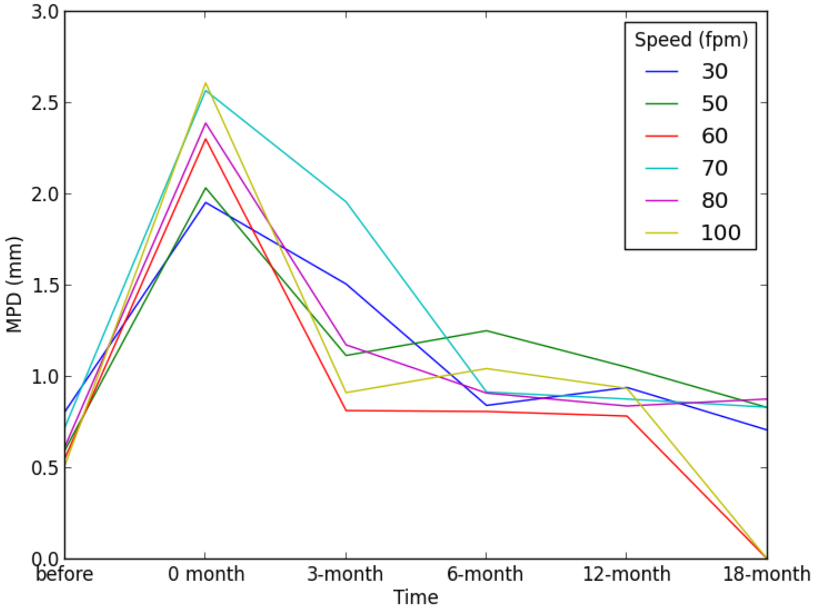


Figure 52. Macrotexture versus time for different forwarding speeds (seal coat surface)

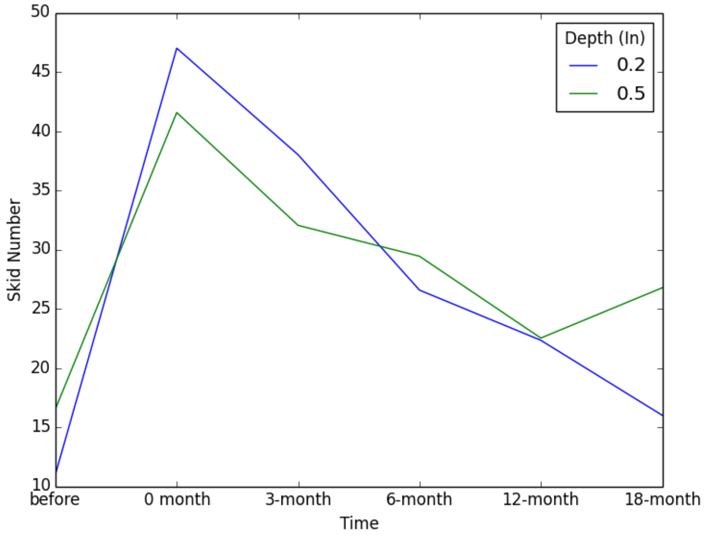


Figure 53. Skid number versus time for different cutting depths

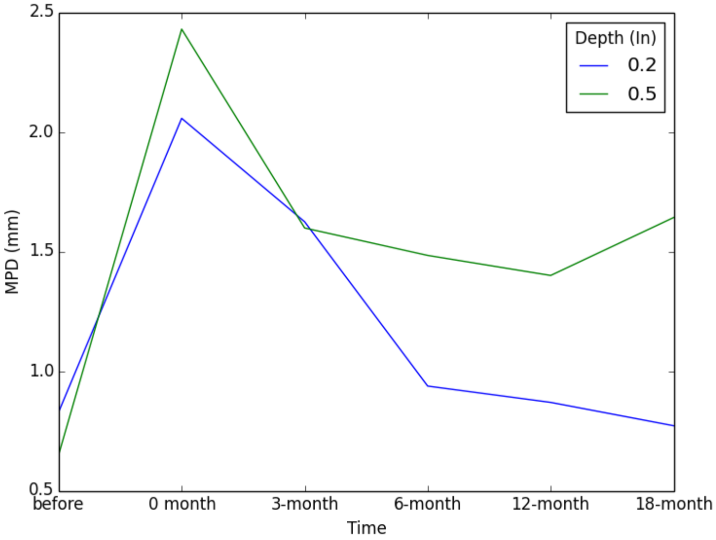


Figure 54. Macrotexture versus time for different cutting depth

5.3 Life Cycle Cost Analysis

According to the data collected in this study, the life of a light texturing treatment is not as long as the expected life of a seal coat or a HMA overlay. It is important to know if it can still be cost-effective to apply this treatment. A life-cycle cost analysis is one way of comparing the costs of different strategies associated with maintaining a pavement facility over an analysis period. Four strategies were chosen for the life-cycle cost analysis in this section. These alternatives were determined by the research team in response to the findings of the skid resistance testing.

- Strategy 1: Only HMA overlay is used during the analysis period
- Strategy 2: Only seal coat is used during the analysis period

- Strategy 3: Light texturing and HMA overlay are used during the analysis period
- Strategy 4: Light texturing and seal coat are used during the analysis period

In the first two strategies, as presented in Figure 55, a treatment of either HMA overlay or seal coat will be applied periodically at an interval of T years, where T is the expected service life of the treatment. The unused life, $T - r$, of the treatment at the end of the analysis period is considered as the salvage value of the strategy.

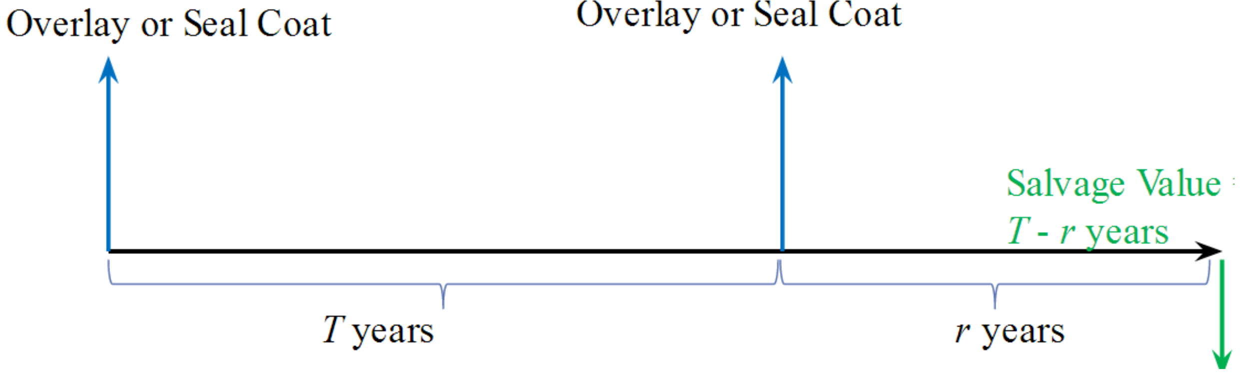


Figure 55. Expenditure stream diagram for strategy 1 and 2

In the third and fourth strategies, a light texturing treatment with expected service life of t years is applied periodically followed by a HMA overlay or seal coat. The salvage value is calculated in a similar way as for strategies 1 and 2. The expenditure stream diagram associated with these strategies is shown in Figure 56. In the life cycle cost analysis, all project costs were discounted to the initial base year using the discount rate i. Discount rate is the rate by which future costs (in dollars) will be converted to present value or base year value. The discount rate used in the life-cycle cost analysis is approximately the difference of the interest rate minus inflation rate.

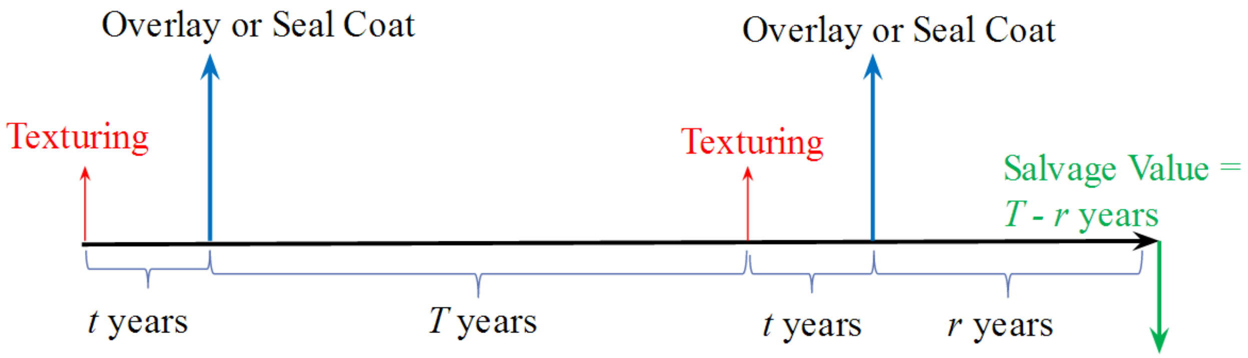


Figure 56. Expenditure stream diagram for strategy 3 and 4

The following information are used in the life-cycle cost analysis. The light texturing pavement milling was paid for at a unit price around $0.50 per square yard. The unit price was full payment for milling, sweeping and clearing; for disposal of surface materials; and for all labor, tools, equipment and incidentals.

- 2 inch HMA Overlay:
    - $50,000 per lane mile
    - Expected life: 10 years
- Seal coat:

  - $15,000 per lane mile
  - Expected life: 7 years
- Texturing:
  - $0.50 per square yard
  - 1 year expected service life for seal coat surface
  - 2 years expected service life for HMA surface

Equivalent Uniform Annual Cost (EUAC) was calculated to compare different strategies. EUAC is determined by converting all costs to a uniform recurring annual cost over the analysis period.

$$EUAC = NPV \times i \times \frac{(1+i)^n}{(1+i)^n - 1}$$

where NPV represents Net Present Value, which discounts all costs to the base year cost. n represents the analysis period.

A life-cycle cost analysis based on TxDOT historical cost was carried out on the four strategies discussed above. With the discount rate being 4%, the cost analysis showed that the first strategy with overlay of an estimated life of 10 years has an equivalent uniform annual cost (EUAC) of approximately $6,165 per lane mile. The second strategy of seal coat with estimated life of 7 years has EUAC of $2,508 per lane mile. The strategy of combining light texturing and overlay together has an EUAC of $5,272 and the last strategy has an EUAC of $2,699. This implies that applying light texturing to delay a HMA overlay project would cost about 15% less than placing the overlay directly. As shown in Figures 57 and 58, the difference between strategies 2 and 4 is small with the fourth strategy performing slightly better than the second strategy. Overall, the analysis suggests that delaying overlay placement for a few years with a light texturing can keep the skid resistance at a reasonable level and save money at the same time. The light texturing method, therefore, appears to be cost effective as a short term correction technique for pavement with skid problems. This would be particularly useful in situations where there are many competing lane miles for limited resources. It would also alleviate an immediate concern while a more permanent solution is planned.

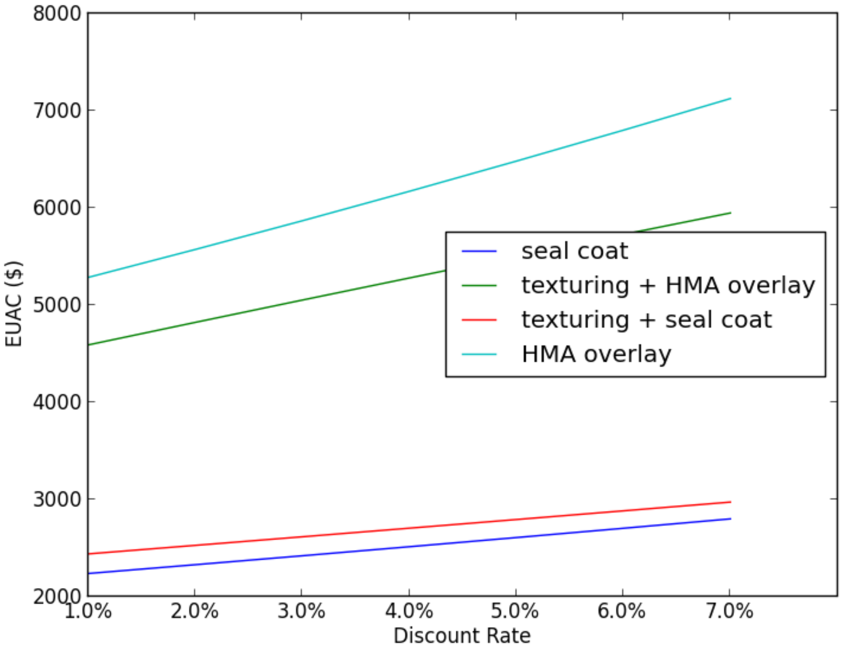


Figure 57. Life-cycle cost analysis using different discount rates

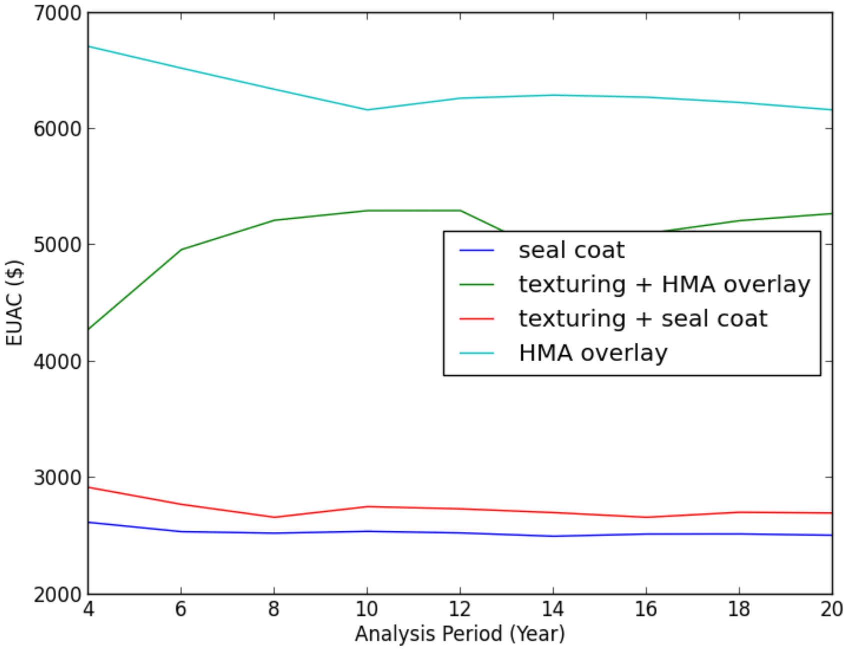


Figure 58. Life-cycle cost analysis using different analysis periods

5.4 Statistical Analysis

A through statistical analysis is necessary 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 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.

5.4.1 Model Development

The researchers employed multiple linear regression analysis for performing statistical inference based 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 months, 6 months, 12 months 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}: 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.

t: Time of measurement.

Z: Vector of interaction variables of the time and the milling features.

β_0: Intercept term
β_1 to β_5 and α_1 to α_2: Regression coefficients
δ: Vector of regression coefficient corresponding to the interaction terms
ε_{it}: Idiosyncratic error term

5.4.2 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. Table 7 and 8 show the statistically significant multiple linear regression model coefficient estimates along with their standard deviations corresponding to both skid resistance and macrotexture respectively.

Table 7. 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 X Time	0.29	0.14	2.14	0.03
Interaction: Seal Coat X Speed	-0.14	0.04	-3.36	0.00
Interaction: Fine Drum X Time	-0.80	0.14	-5.60	0.00

Table 8. 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 X Time	-0.05	0.009	-5.17	0.00
Interaction: Seal Coat X 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 7 and 8. 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.

5.4.3 Synthesis of Analysis Results

The positive and negative signs of the coefficients in Tables 7 and 8 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 shown in Table 7 (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 8. 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. Figure 59 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. (24) also reported a lack of correlation between macrotexture and skid resistance. They emphasize the collective role of macrotexture and microtexture on skid resistance.

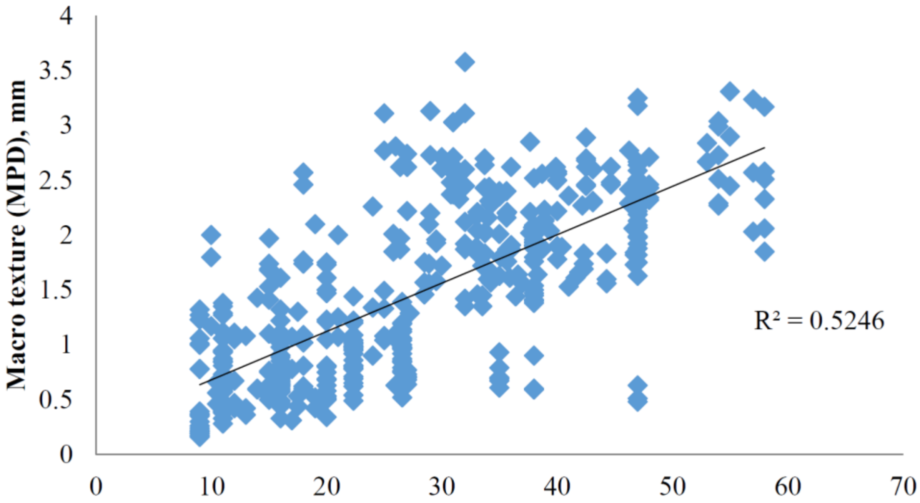
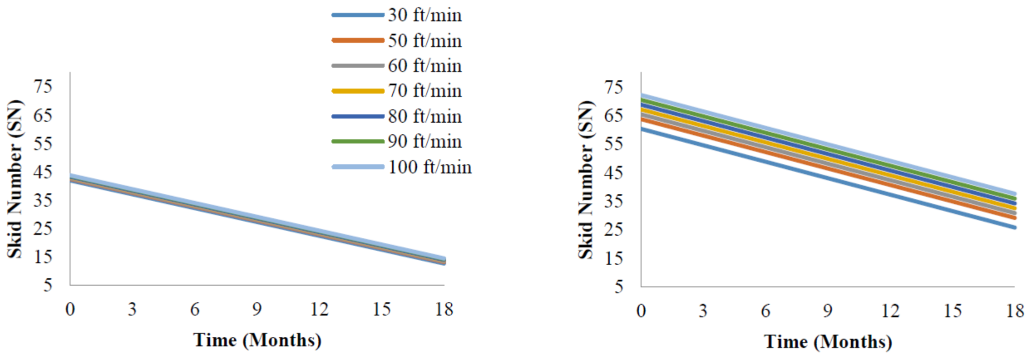
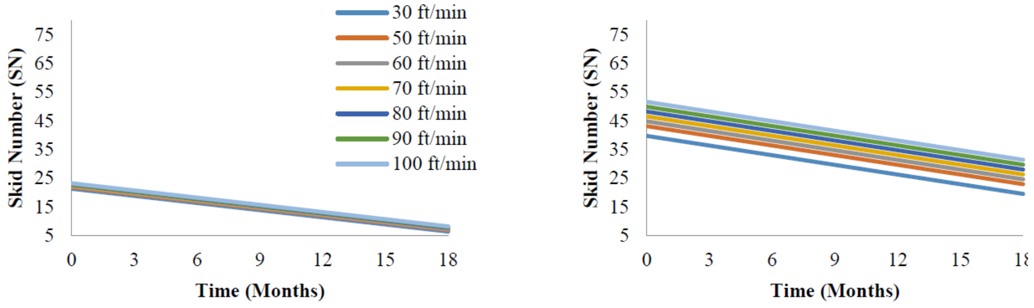


Figure 59. Skid number versus macrotexture after milling

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 x time in Table 1 (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 8 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. Figures 60 and 61 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.

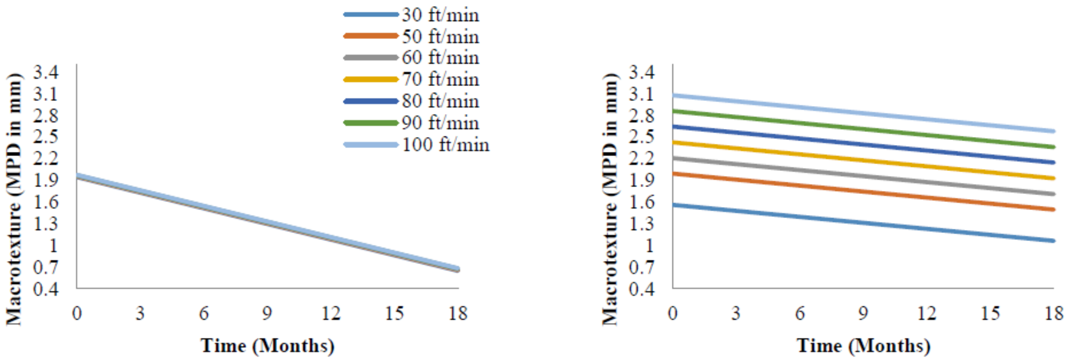


2a Seal coat milled with finer drum *2b HMA milled with finer drum*



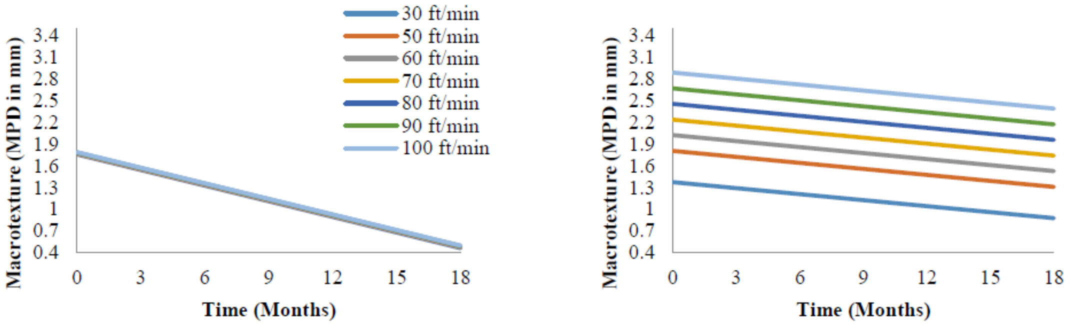
2c Seal coat milled with standard drum *2d HMA milled with standard drum*

Figure 60. Deterioration of skid resistance



3a Seal coat milled with finer drum

3b HMA milled with finer drum



3c Seal coat milled with standard drum

3d HMA milled with standard drum

Figure 61. Deterioration of macrotexture

Influence of Drum Type

The positive sign of the coefficient corresponding to the fine drum indicator variable indicates that sections milled with fine drums exhibited a higher skid resistance after milling as shown in Table 7. 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 8 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.

Influence of forward milling speed

The modeling results shown in Tables 7 and 8 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 Figures 60 and 61. 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.

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.

Chapter 6. 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 forwarding speed helps create the texture qualities needed for higher level friction on HMA surface. Although the speeds of 90 and 100 feet-per-minute (fpm) can produce the highest levels of skid resistance on the test sections, they are highly prone to creating objectionable grooves to the motorcyclists. Forwarding 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.

- Light texturing appears to improve the skid resistance of pavement 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.

- According to the life-cycle cost analysis, delaying an overlay placement by light texturing via a milling machine can be more cost-effective than applying the overlay directly.

- 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 light 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.

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