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Relationship of Aggregate Texture to Asphalt Pavement Skid Resistance Using Image Analysis of Aggregate Shape

Final Report for Highway IDEA Project 114

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by

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ABSTRACT

Aggregate properties are one of the important factors that influence the asphalt pavement skid resistance. This study presents a detailed analysis of aggregate texture and its relationship to pavement skid resistance. A new method is developed for the evaluation of aggregate resistance to polishing. This method relies on the Micro-Deval test as the mechanism for polishing aggregates and the Aggregate Imaging System (AIMS) for quantifying the change in texture due to polishing. The results show that the Micro-Deval test is an effective method for polishing aggregates within a short time. Also, the AIMS texture analysis is able to rapidly and accurately quantify the influence of polishing on texture.

The verification of the new method was achieved through measuring the skid resistance of pavements constructed using three different aggregate sources and three different aggregate gradations. The skid resistance was found to be related not only to average aggregate texture, but also to the texture distribution within an aggregate sample. The developed method can be used in models for predicting the change in asphalt pavement skid resistance as a function of aggregate texture, mixture properties, and environmental conditions.

KEY WORDS: Skid Resistance, Aggregate, Texture, Micro-Deval, Imaging, Polishing

INTRODUCTION

The skid resistance of a pavement is an important property to consider when designing a hot mix asphalt (HMA) mix due to the high correlation between low skid resistance and accident rates (*1*). Wet weather accident reduction programs have been initiated in several states with a focus on the skid resistance of pavements. Kamel and Musgrove (*2*) noted a 54 percent reduction in wet weather accidents and 29 percent reduction in overall accidents when a pavement with a high skid resistance was used. The skid resistance of a pavement surface has been related to two main properties of the pavement, namely microtexture and macrotexture. Dahir (*3*) and Forster (*4*) referred to 0.5 mm as a dividing line between macrotexture and microtexture of the HMA surface. Microtexture is mainly dependent on aggregate shape characteristics and mineralogy, while macrotexture is a function of mix properties, compaction method, and aggregate gradation (*5*, *6*).

There are many studies that relate pavement microtexture to aggregate properties. Bloem (*7*) stated that aggregates that resist polishing and wear are desired to improve skid resistance. Dahir (*3*) and Kamel and Musgrove (*2*) reported that microtexture is mainly determined by texture, abrasion resistance, and petrography of aggregates. Forster (*4*) studied the texture of aggregate using image analysis methods and found it to be related to aggregate friction measured using the British pendulum. Diringer and Barros (*8*) indicated that the polishing characteristics of aggregates become important in affecting skid resistance when the asphalt matrix is sufficiently worn by traffic to expose the aggregate surface. According to Abdul-Malak et al. (*9*) and Crouch et al. (*10*), coarse aggregates at the surface are the main source of HMA pavement surface texture, and developing contacts points between HMA surface and the tire. Prowell et al.

(*11*) stated that some aggregates can be resistant to abrasion while others abrade polished grains away to expose fresh, unpolished grains to allow for higher microtexture.

Macrotexture is related to the height, width, angularity, and density of macro projections from the pavement (*2*). Stephens and Goetz (*1*) studied the relationship between aggregate size and skid resistance, and they found the skid resistance to increase with a decrease in fineness modulus. Hanson and Prowell (*12*) measured the macrotexture using the circular laser texture meter and sand patch method and found this to be highly correlated to fineness modulus. Prowell et al. (*11*) indicated that the gradation of a mix is one of the most important factors in determining macrotexture. Liu (*13*) found an optimum gap for the distance between aggregates at which skid resistance is at maximum.

There are many methods available for measuring aggregate polishing resistance. The most widely used is the British pendulum/wheel method (American Society for Testing and Materials [ASTM] E303 and ASTM D3319). However, many studies showed that the polish value (PV) measured using the British pendulum is a function of many other factors besides aggregate texture (*14*). These factors include the coupon curvature and aggregate size. In addition, most of the PV results of this test, even for a wide range of aggregates, vary within a small range of 4 PV (*15*, *16*), which makes it difficult to distinguish the better performing aggregates. Perry et al. (*17*) studied the PV test and concluded that it is not a good test to predict the skid resistance of aggregates. Smith and Fager (*18*) pointed out some issues regarding the use of the British pendulum as a measure of polishing. They reported that changing the pendulum pad changes the results, although the two pads used in the study met the specification.

Mullen et al. (*19*) suggested two different laboratory methods for evaluating aggregate polishing: the circular track wear method and the jar mill wear method. These two methods rely on using the British pendulum to obtain the PV of pavement samples after polishing either the pavement or the aggregate. Nitta et al. (*20*) used the Penn State reciprocating polishing machine method for measuring aggregate polishing. The machine applies a rubber pad back and forth over a specimen surface to be polished, while water and abrasive are charged to the specimen surface. Crouch and Dunn (*21*) developed a method that relies on using the Micro-Deval machine to polish an aggregate sample for 9 hours, and then the uncompacted voids content apparatus to assess the change in aggregate texture due to polishing.

OBJECTIVES AND TASKS

The main objective of this study was to develop experimental and analysis methods for the evaluation of the relationship between coarse aggregate texture and asphalt pavement skid resistance. This objective is achieved through the following tasks:

1. Developing a new method for measuring the resistance of aggregates to polishing. This method relies on the Micro-Deval test as the mechanism for polishing aggregates and the Aggregate Imaging System (AIMS) for measuring texture.
2. Measuring texture of a wide range of aggregates in order to identify the *distribution* of the *different scales of texture* (i.e., coarse versus fine texture) and their contribution to skid resistance.
3. Measuring the skid resistance of pavements constructed using different aggregate sources and gradation.
4. Relating coarse aggregate texture to pavement skid resistance.

LABORTATORY EVALUATION OF AGGREGATE RESISTANCE TO POLISHING

The new method for measuring aggregate resistance to polishing consists of three steps: 1) measure the initial aggregate texture, 2) polish the aggregates, and 3) measure the texture after polishing. In this study, aggregate texture before and after polishing is measured using the Aggregate Imaging System. AIMS determines shape characteristics of aggregates through image processing and analysis techniques (*22*). AIMS is a computer automated system that includes a lighting table where aggregates are placed in order to measure their physical characteristics (shape, angularity, and texture). It is equipped with an autofocus microscope and a digital camera, and is capable of analyzing the characteristics of aggregate sizes retained on sieve #100 (0.15 mm) up to aggregates retained on a 1-inch sieve (25.4 mm). The focus of this study is on measuring the shape characteristics of coarse aggregates retained on sieve #4 (4.75 mm) since previous research has shown that coarse aggregates influence skid resistance of HMA pavements much more than fine aggregates (*6*, *9*).

AIMS gives a measure of aggregate angularity by analyzing the irregularity of a particle surface using the gradient method (angularity index) and the three-dimensional shape. However, these properties were not found to have a relationship with the measured skid resistance of the pavement sections evaluated in this study, and they are omitted here for brevity (*23*). The AIMS texture is measured by analyzing grayscale images captured at the aggregate surface using the wavelet analysis method (*24*). This method analyzes the image as a two-dimensional signal of grayscale intensities, and it gives a higher texture index for particles with rougher surfaces. It takes about 10 minutes to analyze the texture of a coarse aggregate sample that consists of 56 particles. The AIMS texture method is capable of analyzing six different scales of texture on a single particle surface. Level 1 corresponds to the smallest scale texture (finest texture), while level 6 corresponds to the largest texture scale (coarsest texture). As reported by Luce (*24*), based on analyzing more than 100 aggregate sources, the results from levels 1 and 2 were not able to discriminate among the different aggregate sources, and they are highly affected by image noise. Level 3 had very high positive correlation with level 4. Therefore, the analysis of this study will focus on levels 4, 5, and 6. All details of AIMS and the analysis principals are given by Al-Rousan (*23*).

The Micro-Deval test was used as the mechanism for polishing aggregates in this study. In this test, coarse aggregates are tumbled together with steel balls in the presence of water in a drum (*25*). The test is standardized in the American Association of State Highway and Transportation Officials (AASHTO) T 327-05 procedure and in the Texas Department of Transportation (TxDOT) Tex-461-A procedure, "Degradation of Coarse Aggregate by Micro-Deval Abrasion." The Micro-Deval test was conducted in this study according to the Tex-461-A procedure, which differs slightly from the AASHTO T 327-05 procedure in aggregate size gradation and abrasion time. The aggregate sizes and weights are shown in Table 1. An example of the polishing effect in the Micro-Deval is evident in Figure 1. This figure clearly shows that the Micro-Deval test is able to polish aggregate surfaces.

TABLE 1 Micro-Deval Gradation

Passing	Retained On	Specification
1/2 inch	3/8 inch	750 ± 5 g
3/8 inch	1/4 inch	375 ± 5 g
1/4 inch	#4	375 ± 5 g
Total		1500 ± 5 g

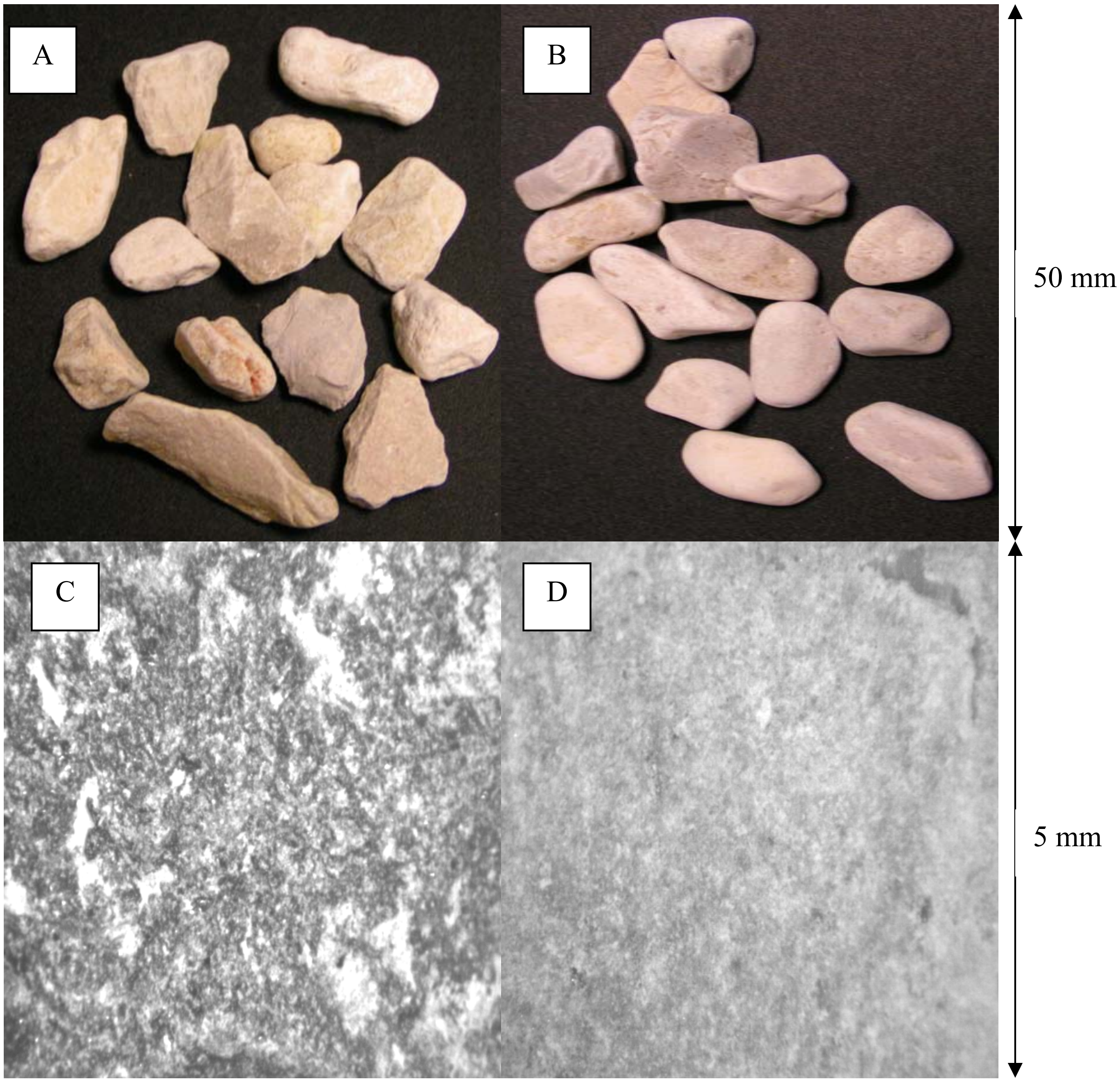

FIGURE 1 Aggregate images: A) aggregate particles before Micro-Deval, B) aggregate particles after Micro-Deval, C) aggregate surface texture before Micro-Deval, and D) aggregate surface texture after Micro-Deval.

The new test method was used to measure the texture of 62 samples of gravel, sandstone, and limestone aggregates. The AIMS measurements were conducted on 56 particles from each of the sizes listed in Table 1. There was no significant difference in the texture results of the three sizes. Therefore, all the results presented here are averaged for the three sizes before Micro-Deval testing (BMD) and after Micro-Deval testing (AMD). By looking at Figure 2, it can be seen that the texture results BMD (Figures 2a and b) are higher than the texture results AMD (Figures 2c and d). These results confirm that AIMS is capable of quantifying the change in texture duo to polishing in the Micro-Deval test. The results also show that the values for the texture levels 4 or 5 (fine texture) are higher than level 6 (coarse texture) for the sandstones. However, the majority of the limestone and gravel samples exhibited a level 6 texture that is either equal or greater than texture level 4 or 5. In other words, the texture of the sandstone aggregates used in this study is finer than the texture of most of the gravel and limestone aggregates tested.

The texture coefficient of variation (COV) was also calculated to determine the variability within each of the aggregate samples, and the results are shown in Figure 3 for each level of texture and both BMD and AMD. It can be seen that there is a wide range of variation in texture among the aggregate samples. In general, the sandstones had a lower COV when compared with the other aggregate types. This indicates that the texture variability within an aggregate sample is an important factor that needs to be taken into consideration. These results lead to two questions that need to be answered: 1) What are the texture levels that affect asphalt pavement skid resistance? 2) What is the role of texture variation within an aggregate source on asphalt pavement skid resistance?

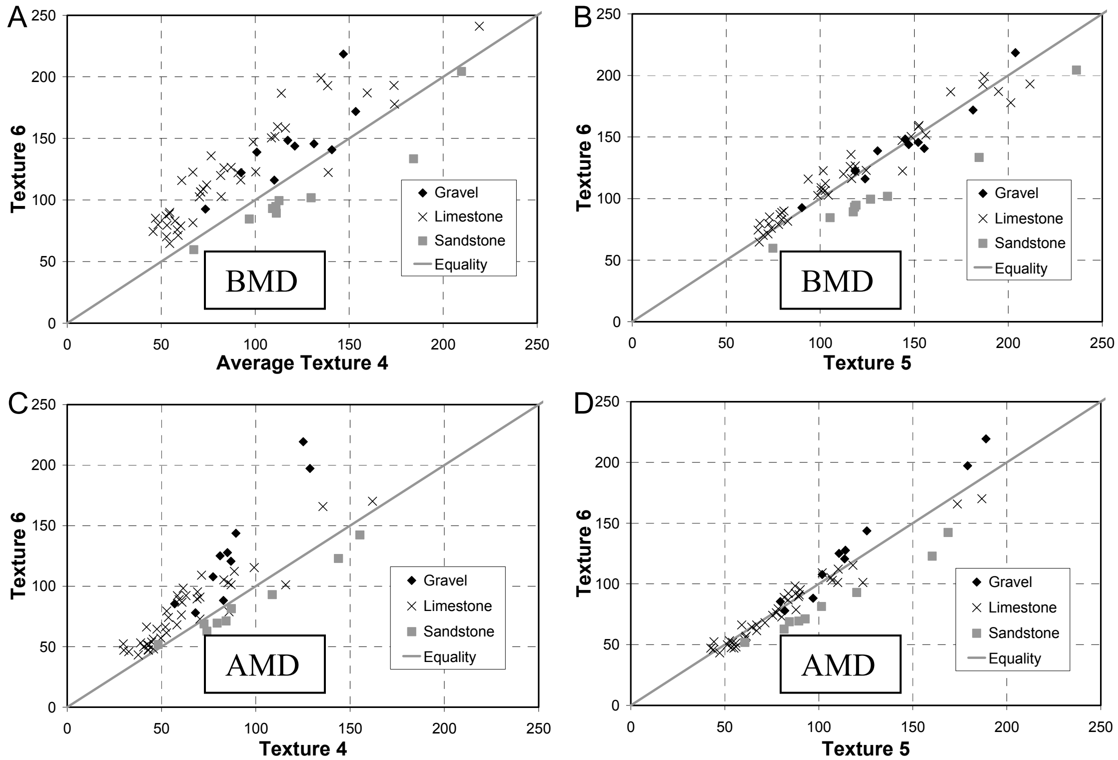

FIGURE 2 AIMS texture level 6 comparison versus A) level 4 BMD, B) level 5 BMD, C) level 4 AMD, and D) level 5 AMD

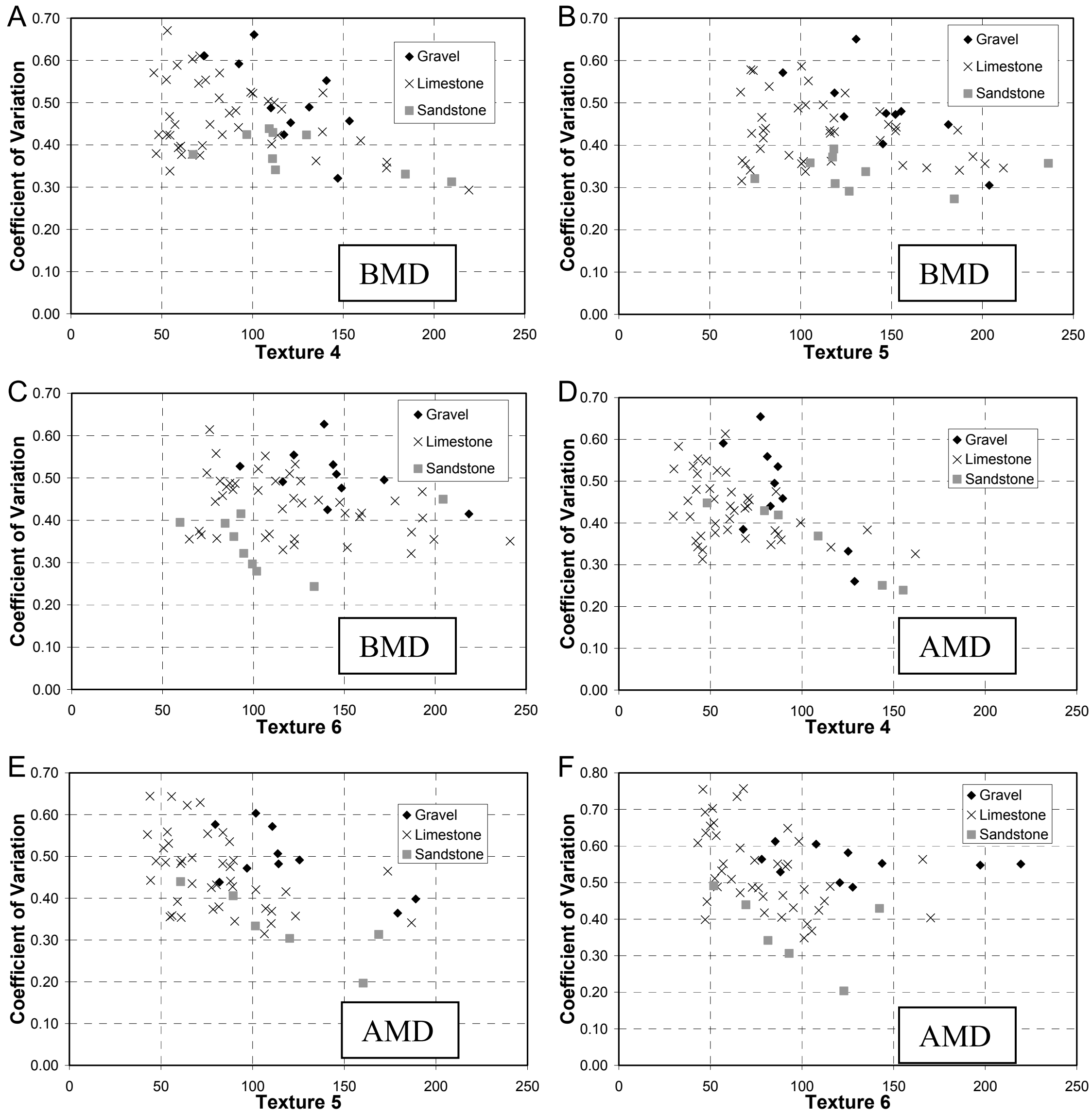

FIGURE 3 COV in texture for A) level 4 BMD, B) level 5 BMD, C) level 6 BMD, D) level 4 AMD, E) level 5 AMD, and F) level 6 AMD.

RELATIONSHIP OF AGGREGATE TEXTURE TO PAVEMENT SKID RESISTANCE

Asphalt Mixtures

An experiment was conducted to determine the relationship between aggregate texture and asphalt pavement skid resistance. Nine pavement test sections were evaluated in this experiment. These test sections were constructed in late 2000 as part of a project to rehabilitate IH-20 in Harrison County in northeast Texas (*26*). The specific location of these sections is from 0.5 miles west of FM 3251 to 0.5 miles east of SH 43. The nine test sections consist of three different aggregate types: quartzite, sandstone, and siliceous gravel, combined in three different mix types that are referred to as CMHB-C, Superpave, and Type C. CMHB-C is a dense graded mixture used by TxDOT. It is designed to have a relatively large amount of coarse aggregate and relatively high binder content. Type C is also a dense graded mixture relatively finer than the CMHB-C mixture. The Superpave mixture used in this study is a ½-inch Superpave mixture gradation passing below the restricted zone. Table 2 denotes the section numbers and the corresponding mix and aggregate properties. The pavement structure consisted of previously repaired continuously reinforced concrete pavement (CRCP) overlaid with a 2-inch thickness asphalt base with a fabric interface between them, and then finally the surface course with an average thickness of 2 inches. All of the mixes used the same PG 76-22 asphalt. The mixes were designed to carry 30 million equivalent single axle loads (ESALs).

Pavement Skid Measurements

The skid measurements were taken using a skid trailer following ASTM E274-97, “Standard Test Method for Skid Resistance of Paved Surfaces Using a Full Scale Tire.” Using this method, a trailer of known weight is pulled along the roadway. As the trailer is pulled, one of the tires, typically the left, is locked. Water is applied to the roadway shortly before the tire is locked to allow for a measurement under wet conditions. For the measurements in this study, the test was conducted at 50 miles per hour. The force required to pull the trailer is then measured. The skid resistance of the pavement is quantified by the skid number using Eq. (1), which gives a measure of the steady-state friction force.

$$SN = (F/W) \times 100 \qquad (1)$$

where F is the force (lb) required to pull the trailer and W is the weight (lb) of the trailer.

The skid resistance of the pavement sections had been measured twice since construction. The first set of skid measurements were taken during the summer of 2004. The second set of skid measurements were taken in late November of 2005. During this second set of measurements, the outside lane and the outside shoulder were both tested. Since the initial skid measurement right after construction was not performed, the skid measurements on the shoulder were considered to represent the reference point or initial conditions of the pavement skid resistance. The skid measurements were taken about every 0.5 miles for the summer 2004 measurements and 0.1 miles for the other testing period, which resulted in between two and six measurements within each pavement section. The pavement sections' skid results are shown in Figure 4. The maximum standard deviation was about 4.72 skid numbers. The results for skid are also tabulated by aggregate and mix type in Table 3. In general, the skid number decreased with time. In some cases, however, the summer 2004 measurements had the lowest skid number. This can be attributed to the variation of skid resistance within the pavement section since skid measurements were not taken at the same exact locations in summer 2004 and November 2005. Also, seasonal variations influence the skid resistance throughout the year; it has been reported that skid resistance is normally the lowest near the end of the summer (*27*).

TABLE 2 Aggregate and Mix Type for IH-20 Test Sections

Property	Section Number								
	1	2	3	4	5	6	7	8	9
Mix Type	Superpave			CMHB-C			Type C		
Aggregate	Siliceous Gravel	Sandstone	Quartzite	Siliceous Gravel	Sandstone	Quartzite	Siliceous Gravel	Sandstone	Quartzite
Design Asphalt Content	5.0	5.1	5.1	4.7	4.8	4.8	4.4	4.5	4.6
Target Design Percent Air Voids (%)	4.0	4.0	4.0	3.5	3.5	3.5	4.0	4.0	4.0
Voids in Mineral Aggregate (VMA) (%)	15.3	15.1	15.6	14.1	14.6	14.1	14.0	14.1	14.6
Gradation									
Sieve Size	Percent Passing (%)								
7/8	--	--	--	100.0	100.0	100.0	100.0	100.0	100.0
¾"	100.0	100.0	100.0	--	--	--	--	--	--
5/8"	--	--	--	99.7	100.0	99.6	100.0	99.8	99.8
1/2"	92.0	92.1	93.7	--	--	--	--	--	--
3/8"	84.8	79.4	81.7	64.5	65.4	65.6	75.8	80.7	79.1
#4	52.4	49.0	45.5	34.3	38.0	34.2	49.2	46.2	51.4
#8	30.9	29.2	31.4	--	--	--	--	--	--
#10	--	--	--	21.8	24.0	24.0	31.5	30.9	34.0
#16	20.4	22.4	21.0	--	--	--	--	--	--
#30	13.9	18.9	17.7	--	--	--	--	--	--
#40	--	--	--	16.2	16.4	14.5	18.2	15.6	17.9
#50	8.8	14.9	11.8	--	--	--	--	--	--
#80	--	--	--	9.8	10.9	9.1	11.7	9.6	10.0
#100	4.5	10.2	8.2	--	--	--	--	--	--
#200	3.2	6.5	5.6	6.4	6.4	5.9	5.8	5.8	5.3
Composition									
Material	Percent (%)								
Percent of Primary Aggregate	67	91	89	79	87	87	61	99	91
Percent of Igneous Screening	0	8	10	20	12	12	8	0	8
Percent of Limestone Screening	32	0	0	0	0	0	30	0	0
Percent of Lime	1	1	1	1	1	1	1	1	1

Based on the results in Table 3, a trend can be noticed between aggregate type and skid resistance. The sandstone clearly had the highest skid resistance, with quartzite second and gravel last. In most cases, all mix types for a given aggregate source had nearly the same skid resistance, except for the summer 2004 where the gravel Type C mix measurement was considerably lower than that of the others.

Analysis of variance (ANOVA) at a significance level of 0.05 was used to test the significance of both the aggregate type and mix type on the value of skid number using the statistical package SPSS version 11.5. The results showed that the aggregate type was a statistically significant factor (p-value less than 0.05), while a p-value of 0.089 for mix type indicates that the mix type was not statistically significant. Also, multiple comparisons among the aggregate types showed that the three aggregates are different pair wise. Of course, mix type is an important factor in influencing skid resistance. However, it seems that the mixes used in this study were not different enough in their gradations to influence the measured skid number.

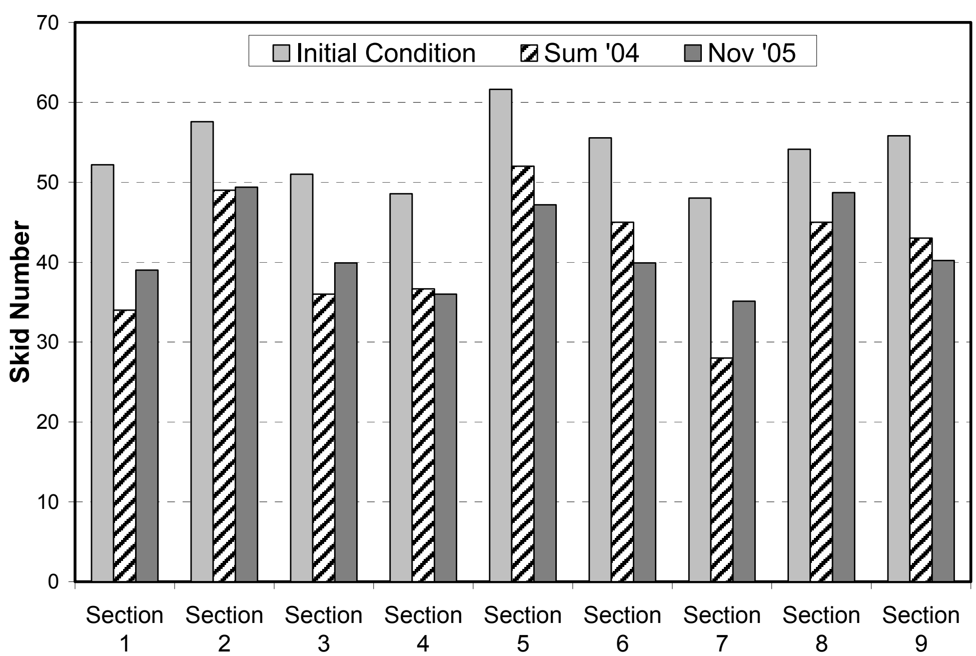

FIGURE 4 Skid results of IH-20 test sections.

TABLE 3 Average Skid Resistance of Test Sections

Measurement Time	Mix Type	Aggregate Type			Average
		Siliceous Gravel	Sandstone	Quartzite	
Initial Conditions	Superpave	52.20	57.57	51.00	53.59
	CMHB-C	48.57	61.63	55.56	55.25
	Type C	48.00	54.13	55.80	52.64
	Average	49.59	57.77	54.12	
Summer 2004	Superpave	34.00	49.00	36.00	39.67
	CMHB-C	36.67	52.00	45.00	44.56
	Type C	28.00	45.00	43.00	38.67
	Average	32.89	48.67	41.33	
November 2005	Superpave	39.00	49.38	39.90	42.76
	CMHB-C	36.00	47.17	39.90	41.02
	Type C	35.11	48.70	40.20	41.34
	Average	36.70	48.41	40.00	

Aggregate Texture Measurements

Typically the Micro-Deval test is run for 105 minutes. However, it was decided to do more detailed analysis through testing aggregate samples in the Micro-Deval for 15, 30, 60, 75, 90, 105, and 180 minutes. AIMS measurements were conducted after each of the time intervals in the Micro-Deval test. The initial texture was almost identical for the different samples from a given source. A total of 168 particles from each aggregate source (56 particles of each of the sizes in Table 1) were measured in AIMS at each of the polishing time intervals.

The results for the three texture levels (4, 5, and 6) are shown in Figures 5a, b, and c. The quartzite aggregate had the most rapid decrease in texture compared with the other two aggregates. Sandstone started with a high texture and retained its texture with time. The gravel aggregate started with a low texture and did not lose much of its texture. Equation 2 was used to describe the change in aggregate texture due to polishing in Micro-Deval as a function of time. In this equation, a, b, and c are all regression constants, while t is the time in the Micro-Deval.

$$\text{Texture }(t) = a + b \times \exp\left(-c \times t\right) \qquad (2)$$

The SPSS 11.5 software was used to fit Eq. (2) to the measurements, and the equation coefficients are shown in Table 4. The fitting of Eq. (2) to the experimental measurements are shown in Figures 5a, b, and c. It can be seen that the equation fit the texture results well. Mahmoud (*16*) conducted statistical analysis of fitting Eq. (2) to texture measurements and determined that only three time intervals (0, 105, and 180 minutes) are sufficient for Eq. (2) to give fitting that is very similar to using nine time intervals, as was done in this study. The advantage of using Eq. (2) is the potential for using it to calculate aggregate texture as a function of time, and then using this texture value as part of a model that can predict skid resistance as a function of different mix properties and time or traffic.

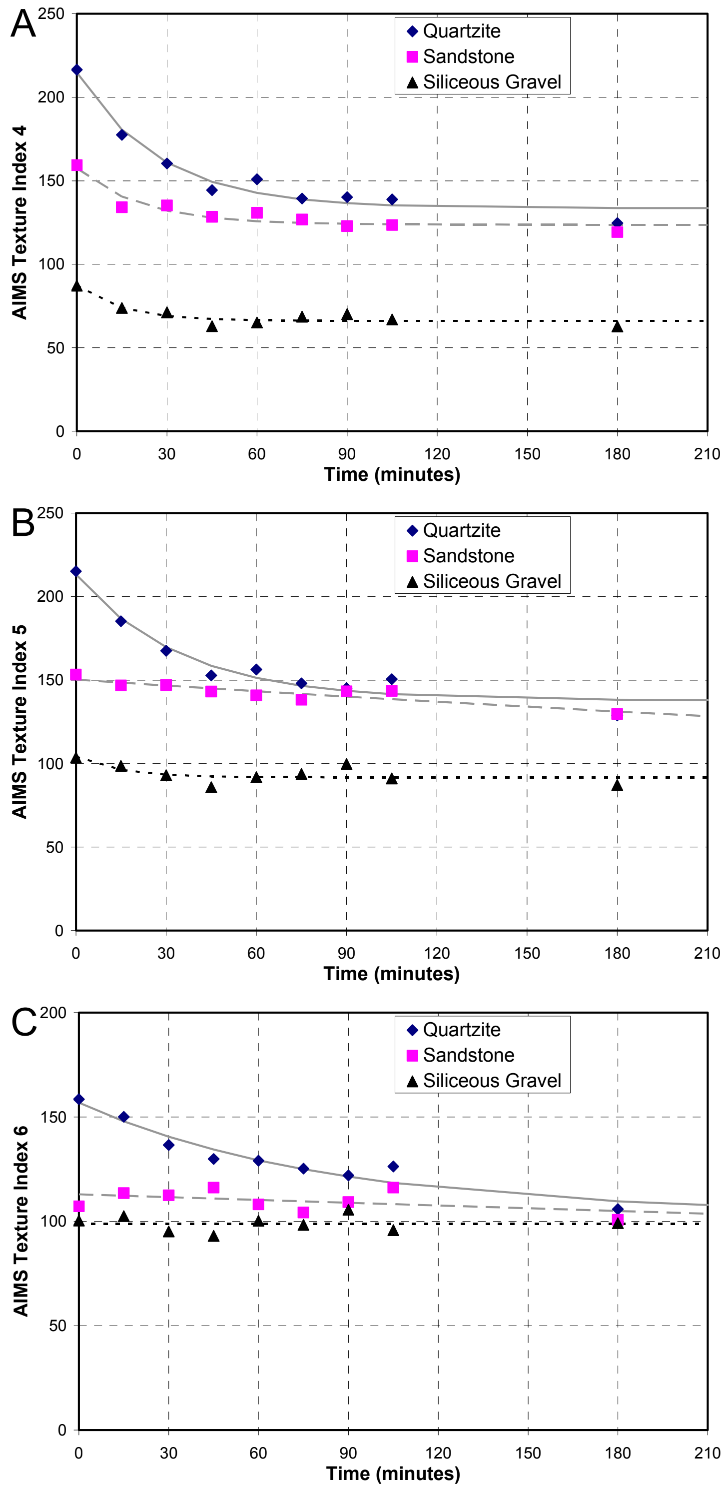

FIGURE 5 AIMS texture index versus time in the Micro-Deval test with regression results for A) texture level 4, B) texture level 5, and C) texture level 6.

TABLE 4 Statistical Results for Texture Curve Fitting

Aggregate	Texture Level	a	b	c
Siliceous Gravel	Level 4	66.19	21.04	0.06738
	Level 5	91.70	12.45	0.06687
	Level 6	49.38	49.54	0.00000
Sandstone	Level 4	123.70	33.69	0.04641
	Level 5	58.66	91.60	0.00130
	Level 6	0.21	112.77	0.00041
Quartzite	Level 4	133.54	81.17	0.03632
	Level 5	137.90	75.32	0.02875
	Level 6	103.67	53.18	0.01219

Analysis of Results

The gravel mixes had considerably less skid resistance than the sandstone and quartzite mixes. This finding is in agreement with the texture analysis results from levels 4 and 5 (Figures 5a and b). Level 6 did not give very good distinction among the aggregates' texture, especially after 45 minutes of polishing (Figure 5c). These results suggest that levels 4 and 5 are more capable of distinguishing aggregates based on texture. The average of these two levels will be adopted to describe aggregate texture in relationship to skid resistance.

The texture results at all levels did not show good distinction between the sandstone and quartzite at the terminal texture levels. However, the pavement skid resistance of the sandstone sections was better than that of the quartzite sections. It is noted that there were only slight differences in aggregate gradation within each mix type (Table 2). Therefore, aggregate gradation does not explain this difference among the mixtures. The coefficient of variation was evaluated here for each of the sets of AIMS measurements after each of the time intervals in the Micro-Deval. Figure 6 shows the comparison between texture and coefficient of variation for each of the three aggregates tested and different texture levels studied. Each of the time steps (0 to 180 minutes) is used as a point for comparison. It can be seen that the sandstone had the lowest variation (most uniform texture) out of the three aggregates tested. Therefore, the uniformity of sandstone texture has contributed to the high skid resistance of the sandstone sections compared with the quartzite sections. In other words, both the average texture value and texture variation are important in influencing skid resistance.

The relationship between texture COV and average texture is plotted in Figure 7, while the skid numbers obtained on November 2005 for the outside lane are shown as labels for the three points. Such a chart can be used to describe the contribution of aggregate texture to skid resistance. An aggregate that is plotted in this chart to the right (high average texture) and to the bottom (low variation) is favorable. Future research will focus on testing more aggregates and skid resistance of pavement sections in order to use the chart in Figure 7 to recommend aggregates with desirable texture characteristics.

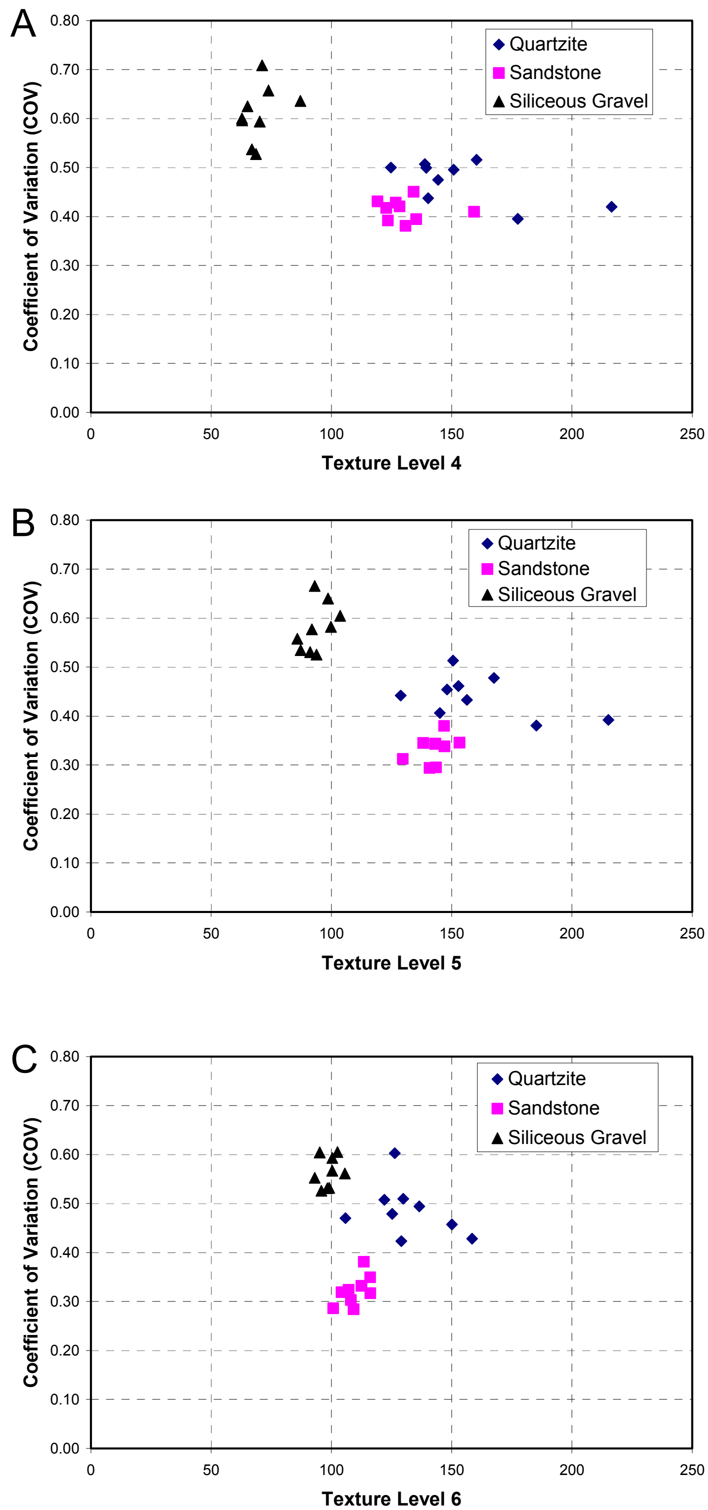

FIGURE 6 COV versus AIMS texture index for A) texture level 4, B) texture level 5, and C) texture level 6.

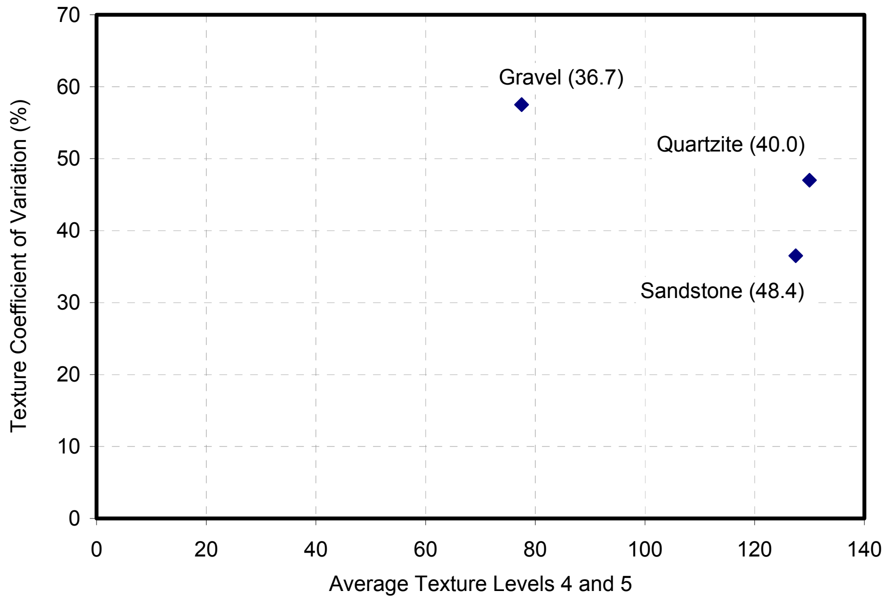

FIGURE 7 A chart for comparing aggregate texture to pavement skid resistance.

SUMMARY

A method was developed for measuring the influence of coarse aggregate texture on asphalt pavement skid resistance. This method has the advantages of 1) polishing aggregates within a time period much shorter than that used in the British pendulum/wheel method (ASTM E303/ASTM D3319), 2) identifying the texture levels that influence skid resistance, and 3) accounting for the variation of texture within an aggregate sample. The method was capable of explaining the differences in skid resistance of pavement sections that were constructed using three different aggregate sources and three different gradations. ANOVA analysis was conducted on skid measurements, and it showed that aggregate type was statistically significant in affecting skid resistance. The developed method can be used by engineers to select the acceptable aggregate texture levels to improve asphalt pavement skid resistance and thereby enhance the safety of motorists, especially in wet weather conditions. Also, it provides information about the change in aggregate texture as a function of time in the Micro-Deval test as shown in Eq. (2). As such, this information can be used in the future to develop a model to predict skid resistance as a function of time, aggregate properties, mix properties, traffic, and environmental conditions.

The researchers are currently conducting a study funded by the Texas Department of Transportation (TxDOT) to verify the findings in this report. In the TxDOT study, the researchers are measuring texture of aggregates from many different sources and measuring the skid resistance of asphalt pavement sections in which these aggregates were used. The experimental design includes mixtures with different gradations, asphalt contents and asphalt grades. The pavement sections are also subjected to different traffic loads.

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