

Identifying Fine Aggregates Prone to Polishing in PCC Pavements

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Abstract

Surface polishing in portland cement concrete (PCC) pavements leads to higher incidences of skid-related accidents on highways. This type of failure is often associated with the usage of softer fine aggregate such as limestone sands. To identify polish resistance aggregates, state agencies like TxDOT have adopted tests such as the acid insoluble residue test (AI). Since calcium carbonate is soluble in acid, no carbonate sand passes the AI test which has a minimum limit of 60% in Texas. This paper describes research that was done to evaluate the polish resistance of aggregates using a laboratory concrete performance test. Concrete slabs made with different fine aggregates were evaluated for skid using a circular track meter (CTM), a dynamic friction tester (DFT), and a three-wheel-polishing device (TWPD). To ensure that the values obtained at the laboratory related to field performance, test sections constructed with 100% limestone sand and blended sands were also evaluated. Results show that some of the aggregates that failed the AI test performed as well as some of the siliceous fine aggregates that passed the AI test. Other aggregate tests such as the micro-Deval have shown to relate more closely to the concrete performance tests performed under laboratory conditions.

Introduction

Natural sands are being depleted in metropolitan areas where the need for concrete is high. In such areas, the concrete industry has the options to either ship natural sands from outside sources or use local sources of manufactured fine aggregates (MFA). The use of local sources of aggregates is usually preferable because shipping aggregates from outside sources adds to the cost of concrete. Using MFAs in PCC pavements can result in several problems including workability, finishability, and skid resistance. These problems exist because of the mineralogy, shape, and grading of MFAs. Workability and finishability may be improved by better proportioning concrete mixtures, but skid resistance is mainly dependent on the mineralogy of the aggregate exposed at the surface. A decrease in skid resistance leads to higher incidences of skid-related accidents on highways. Softer aggregates e.g. carbonate sands, are known to polish when used in PCC pavements and thus provide less long-term skid resistance when compared to harder siliceous sands. No recent research has been done to evaluate skid resistance of PCC made with carbonate sands, and thus it is not clear whether or not current specifications adopted by state agencies accurately reflect the performance of those sands in the field.

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This paper presents the results of a research project that was done to evaluate the skid resistance of concrete made with different sands and blends of sands. The goal of this project was to find a method to better evaluate the polish resistance of fine aggregates used in PCC pavements. The research included both field and laboratory testing. The laboratory and field skid performance of concrete were evaluated using the Circular Track Meter (CTM) and Dynamic Friction Tester (DFT). The results obtained from the concrete laboratory testing were then compared to aggregate tests which included the acid insoluble residue test (AI) and the micro-Deval abrasion test for fine aggregates.

Background

The mineralogy of coarse aggregate is vital for obtaining good skid performance in asphalt concrete. In PCC, however, the mineralogy of the fine aggregate is more important for obtaining good friction. The coarse aggregate only becomes an influencing factor in cases where the top surface of the pavement has been severely abraded or when coarse aggregate is intentionally exposed. Folliard and Smith (2003) identified fine aggregate mineralogy and hardness as important factors for obtaining good surface friction after the texture of a pavement is abraded [4]. Since it is difficult to directly measure the resistance of fine aggregate to polishing, other indicator tests have been used [4]. The most widely used test is the acid insoluble residue test (AI). The test assesses the presence of noncarbonated material in the fine aggregate; materials that have high carbonate content yield low residue because they dissolve in acid, while materials with low carbonate content yield a high residue. It is believed that the presence of acid insoluble material in the sand fraction generally improves skid resistance [4]. In PCC pavements, the fine aggregates exposed on the surface constitute the micro-texture (wavelength < 0.5 mm, amplitude = 1 to 500 μm). Micro-texture is important to maintain adequate friction in dry-weather conditions and wet-weather conditions when speeds are less than 72 km/h (45 mph) [6].

Many states have either banned the usage of carbonate fine aggregates in PCC pavements or have required blending those aggregates with harder aggregates to meet certain limits. In 1958, the need for skid resistant pavements was recognized by the First International Skid Prevention Conference [3]. After this conference, state agencies started developing equipment to test skid both in the laboratory and in the field [3]. In 1958, Shupe and Lounsbury showed a correlation between calcium carbonate content of aggregates and skidding susceptibility [3]. Gray and Renninger (1965) recognized the contribution of siliceous sand particles in skid resistance and pioneered the acid insoluble residue test to analyze the amount of siliceous materials in the aggregates [3]. Balmer and Colley (1966) correlated results of a laboratory concrete skid performance test to the acid insoluble residue of the aggregates tested. They concluded that 25% siliceous fine aggregate content was satisfactory for skid performance with most aggregates. Most specifications base their limits on the study done by Balmer and Colley. Some specifications require a minimum of 25% siliceous sand content in pavement concrete, while other specifications have set limits based on acid insoluble residue (AI) values. The Texas Department of Transportation (TxDOT) originally required fine aggregates to meet an AI limit of 28%, which would have required about 25% siliceous sand content and excluded the usage of 100% carbonate sands. After skid problems were reported, the AI limit was raised to 60%. Under the 60% AI specifications, the maximum amount of carbonate sand that can be used in a PCC pavement is less than 40% of the total sand volume. The adoption of the 60% AI limit by the TxDOT has affected districts like the Dallas and Ft Worth districts that

have limited local sources of natural siliceous sands and have to haul natural sands from distant pits and blend them with their local sources of manufactured carbonate sands to meet the 60% AI limit.

Studies done after 1966 had similar conclusions as the study done Balmer and Colley. Renninger and Nichols (1977) found good correlation between skid resistance (as determined by the British Pendulum Tester) and acid insoluble residue [9]. As part of a study that evaluated micro-texture and macro-texture on PCC pavements around the United States, Hall and Smith (2009) found that tougher, more durable aggregates retain higher friction values. They found that the usage of limestone in Kansas and Illinois resulted in greater rates of micro-texture deterioration compared to the usage of high silica granite aggregates in Minnesota [6]. Figure 1 illustrates the difference between an abraded section made with hard siliceous sand and another made with soft limestone sand.

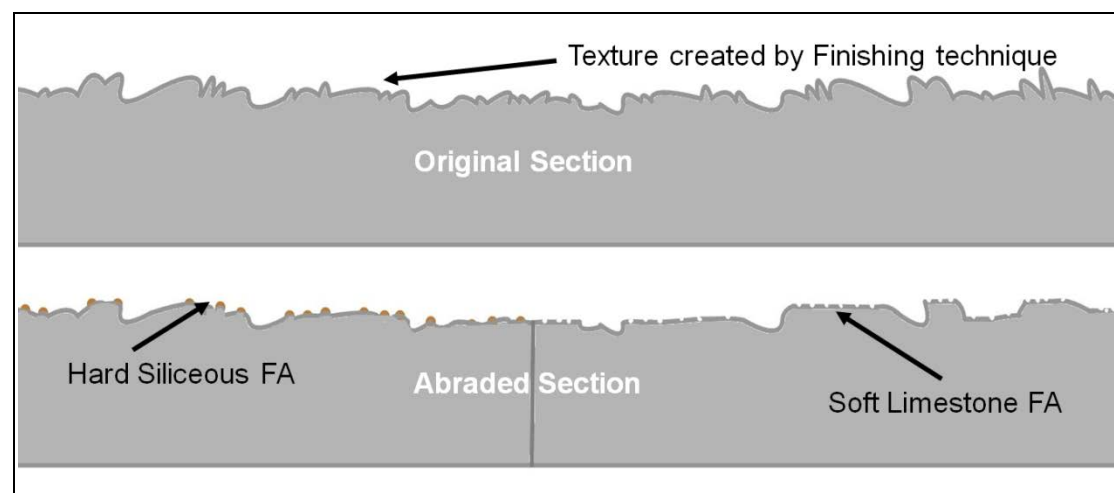


Figure 1. Abraded Concrete Surface Characteristics

The Locked-Wheel Skid Trailer (ASTM E 274) is the most common method used to evaluate skid resistance on pavements in the United States. The method consists of measuring the locked-wheel friction (100% slip condition) of a trailer towed behind a truck at a speed of 64 km/h (40 mph) or 80 km/h (50 mph). The trailer administers a water spray to the pavement in front of the tire to simulate wet conditions. The resulting friction force acting between the test tire and the pavement surface is used to determine the skid resistance which is reported as a skid number (SN). Higher SN values signify higher skid resistance. A smooth tire (ASTM E 524) or a ribbed tire (ASTM E 501) can be used on the skid trailer. Research has shown that ribbed tires are only capable of evaluating the effect of micro-texture on friction, while smooth tires can measure the contribution of micro-texture as well as macro-texture [5, 7]. Some state agencies have trigger skid values that they use as means of initiating some sort of rehabilitation treatment; these values differ from state to state. The most common trigger values reported are SN < 35 or 30 for ribbed tires, and SN < 20 for smooth tires [5]. It is believed that SN values below those limits can result in an increase in skid related accidents on roadways.

The Locked-Wheel Skid Trailer can only be used in the field, for this reason other devices such as the Circular Track Meter (CTM) and the Dynamic Friction Tester (DFT) have been developed to evaluate texture and friction in the laboratory as well as in the field (Figure 2). The Dynamic Friction Tester (DFT) is an apparatus that measures the friction-speed relationship on a pavement surface for speeds ranging

from 0 to 80 km/h (micro-texture). The DFT measures the torque needed to stop three small spring-loaded standard rubber pads rotating in a circular path. The torque measured is then converted to a friction value. Water is also introduced during testing to simulate wet conditions. The Circular Track Meter (CTM) is a device that utilizes a displacement sensor that is mounted on an arm that rotates in a circular path and measures the mean profile depth (MPD) of a pavement (macro-texture). The CTM is a device that can be used in the field and laboratory to evaluate macro-texture.

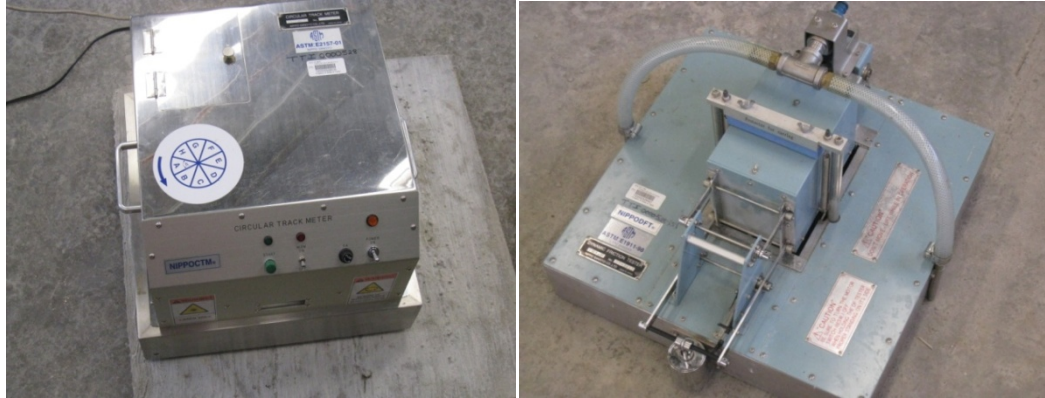


Figure 2. The CTM (left) and the DFT (right)

Values obtained from the DFT and CTM can be used to compute an equivalent skid number (SN). The correlation between different texture and friction devices was established by the Permanent International Association of Road Congresses (PIARC) in 1992 [8]. PIARC developed the International Friction Index (IFI), which is an index for comparing and harmonizing friction measurements with different equipment to a common calibrated index. For example, to compute the equivalent skid number (SN) measured by a locked-wheel skid trailer at 80 km/h (50 mph) using a smooth tire, the following formulas can be used:

$$SN(80)_{smooth} = \left(\frac{F60 - 0.045}{0.925} \times \frac{1}{e^{\frac{20.47}{S_p}}} \right) \times 100 \quad (\text{eq. 1})$$

$$F60 = 0.081 + 0.732DFT_{20}e^{-40/S_p} \quad (\text{eq. 2})$$

$$S_p = 14.2 + 89.7MPD \quad (\text{eq. 3})$$

Where F60 and S_p are the IFI constants, DFT_{20} is the coefficient of friction measured by the DFT at 20 km/h, and the MPD is the mean profile depth value measured by the CTM [2].

Testing Program

Materials and Mixture Proportions. Fifteen sources and six blends of fine aggregates were evaluated in the laboratory. The lithology of the sands used in this research was determined by a petrographer. Nine of the sands tested were siliceous with AI values higher than 60%, while the other six sands were manufactured sands; these included four limestone, one dolomite, and one slate. The reason more siliceous sands were tested was to evaluate how the difference in the acid insoluble residue value affected skid performance. The six blends of sands tested included combinations of siliceous and limestone sands that were blended to meet an AI value of 20%, 40%, and 60%.

Two coarse aggregates were used for the laboratory testing. Both were ASTM C 33 grade 57 limestone coarse aggregates obtained from two adjacent aggregate pits. The reason two sources were used was to include materials from two different producers. Since the coarse aggregate was not exposed in this study, the source of the coarse aggregate had minimal effect on the results. Since there were no indications in the literature that the mixture proportions of concrete (water-to-cementitious ratio, sand-to-aggregate ratio, or paste content) influenced skid resistance, all sands tested in concrete were evaluated using one standard mixture (Table 1).

Table 1. Mixture Proportions used for Evaluating Fine Aggregates

Materials (Volume %)			
Cementitious	Water	Fine Aggregate (SSD)	Coarse Aggregate (SSD)
10.7	14.20	27.1	46.0

The cement used for all mixtures was an ASTM C 150 Type I/II cement. Since the same mixture proportions were used to make concrete specimen using the different sands, a mid-range water reducing admixture was used. This type of admixture is not common for slipform paving mixtures but was used to facilitate casting the concrete specimens. Using a mid-range instead of regular ASTM C 494 Type A water-reducer might affect the workability and finishability of the concrete, but was deemed to have no effect on skid resistance.

Test Methods and Procedures. The acid insoluble residue test used in this research was the test adopted by TxDOT (Tex-612-J). The TxDOT AI test method uses 25 grams of fine aggregates along with a concentrated hydrochloric acid solution [11]. This test is different from the AI test described in ASTM D 3042 which uses a 500-gram sample of fine aggregate along with a diluted (6N) hydrochloric acid solution [1].

All fine aggregates were also tested using the micro-Deval abrasion test. The micro-Deval test (ASTM D 7428) is an aggregate durability test that was extensively investigated and refined by the Ontario Ministry of Transportation. The test consists of placing a pre-soaked aggregate sample (washed and graded) in a jar with a fixed volume of water and a fixed quantity of steel ball bearings. The unit is then put into rotation for a specified period of time or number of cycles. After the sample is run in the device, it is washed over a No. 200 sieve and the retained sample is oven dried. The percent loss in mass is computed from the oven dried sample. Aggregates with a low percent loss are considered to be more durable than the aggregates with a higher percent loss [10].

To be able to evaluate the polish resistance of concrete in the laboratory, a method of simulating abrasion due to traffic was needed. A Three-Wheel Polishing Device (TWPD) developed by the National Center for Asphalt Technology (NCAT) to test asphalt concrete was purchased and modified (Figure 3). The TWPD was developed to be used with a CTM and DFT. It polishes a circular path on a laboratory specimen that has the same diameter as the path evaluated by the CTM and DFT. The NCAT polisher is composed of three wheels that rotate on a laboratory specimen for a specified number of cycles. Circular iron plates can be placed on the turntable to change the weight on the TWPD, and, hence, the stress on the concrete. The TWPD also has a water spray system that sprays water on the surface being polished. NCAT added the water spray system to wash away the abraded particles, simulate wet weather conditions, and to extend the life of the wheels. The modifications made to

the NCAT device included changing the wheels from pneumatic to polyurethane (durometer of 85) and adding a vibration dampener. Each set of polyurethane wheels was replaced after 500,000 polishing cycles. The average stress caused by the wheels on the concrete surface was estimated to be around 50psi (based on the total load and the contact area).



Figure 3. Modified NCAT TWPD

Two slabs 20 in. wide and 3 ½ in. deep were tested for each mixture. The change in texture and friction was monitored over 160,000 polishing cycles using the CTM and DFT. Measurements were taken initially and after 5,000, 40,000, 100,000, and 160,000 polishing cycles. To evaluate the same polished area, each slab was marked so that readings could be taken at the same location. All slabs were textured using a broom finish, and the surface was cured for at least 28 days before the slabs were tested (no curing compounds were used). Two texture readings were measured using the CTM for each slab at each polishing interval. When measuring friction using the DFT, ASTM E 1911 reports that standard deviation on the same test surface for DFT60 is 0.038, and for this reason friction measurements using the DFT at 40,000, 100,000, and 160,000 cycles were repeated several times on the same slab at the same location until the difference between the last two readings was less or equal than 0.01. The last measurement obtained (usually the lowest) was reported.

The CTM and DFT were also used to evaluate field sections. Measurements in the field were taken in the wheel path and between wheel paths. The measurements taken in the wheel path represent the abraded concrete (current condition), while the measurements taken between the wheel paths are good estimates of the original condition of the pavement before it was subject to traffic.

Test Results and Discussion

Test Equipment Correlation. CTM, DFT, and skid trailer measurements were taken on ten different PCC pavements sections to evaluate the correlation between different testing equipment (all ten sections had a carpet drag and tined finish surface). Three to four CTM and DFT measurements were taken in the wheel path of each of the test sections; measurements were taken 30-60 meters apart, depending on how long each section was. A skid trailer equipped with smooth tires was then used to skid the same sections at 80 km/hr. Using equations 1, 2, and 3, the average equivalent skid numbers for each section was computed. Figure 4 shows a comparison between computed skid values and the actual skid values measured using a skid trailer.

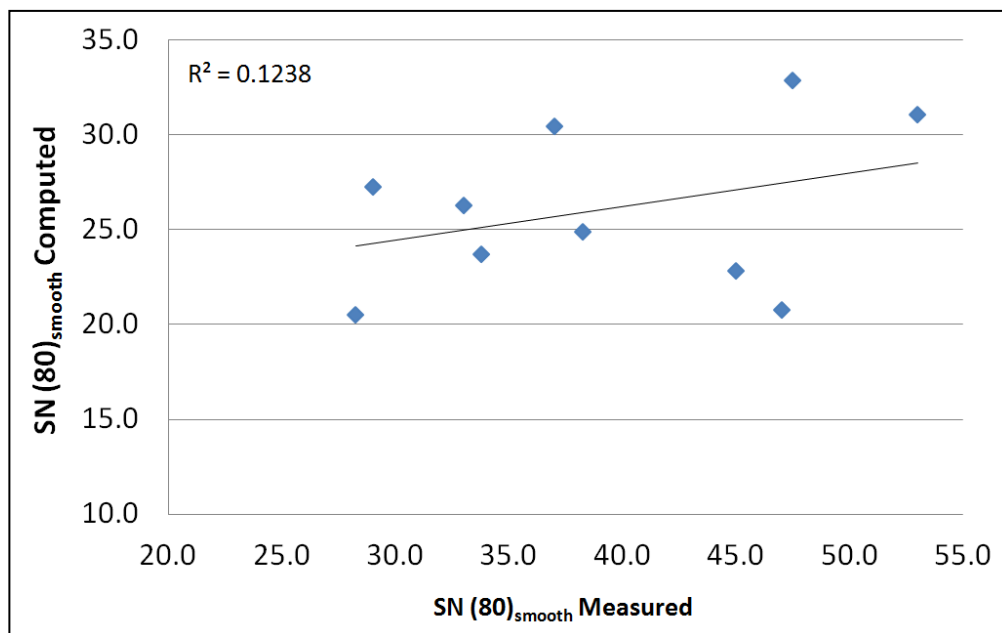


Figure 4. Computed vs. Measured SN(80)_{smooth}

Results from Figure 4 indicate that the IFI formula was not able to predict the actual skid number. A better correlation was obtained when the skid trailer measured values were compared to friction values at 60 km/hr (DFT60). Figure 5 shows that DFT60 results correlate better with skid trailer measured values, and for that reason DFT60 values will be used in this paper to compare performance of field and laboratory tests.

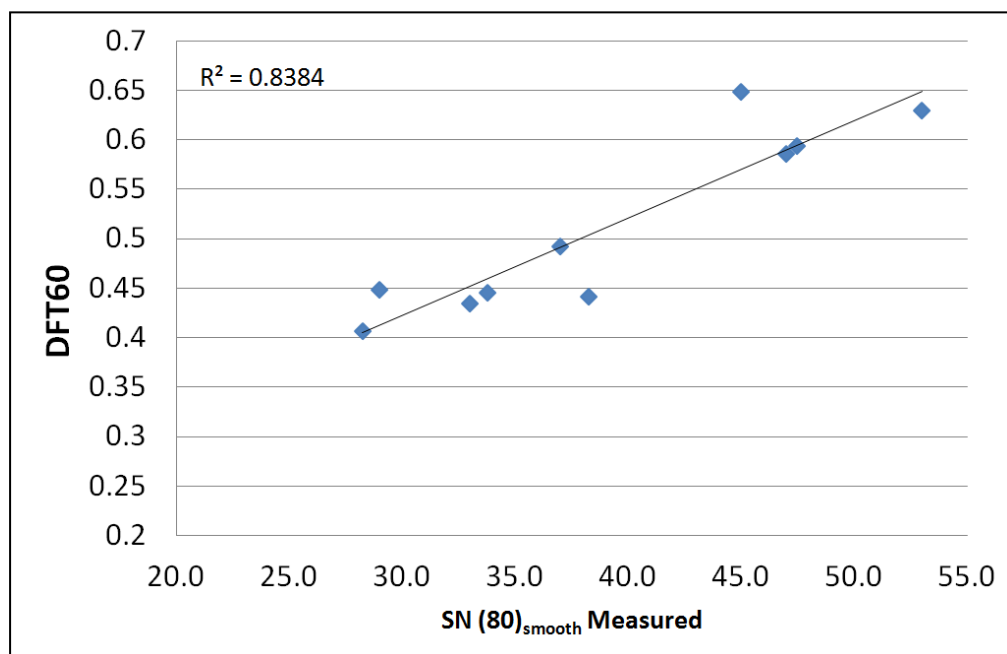


Figure 5. DFT60 vs. Measured SN(80)_{smooth}

Field Testing. Five field sections in two different locations in the Ft. Worth district were evaluated. Those sections were chosen because they were the only known sections in Texas that were made with materials that did not meet the TxDOT AI limit

of 60%. The first location had two sections that were constructed with 100% limestone MFA, while the second location contained three sections made from three different blends of siliceous sand and limestone MFA. The difference between the two sections made with 100% MFA ($AI \approx 0\%$) was in gradation, not source; section 1 had 5% aggregates passing the No. 200 sieve (microfines) while section 2 had 10%. Those two sections were constructed in 2008 as part of an implementation project that involved using manufactured fine aggregates containing high microfines. The other three sections were constructed in 1995 using blends of sands that do not meet the 60% AI limit (AI of 29%, 35%, and 40%). All five sections experience truck traffic; the exact traffic count was not obtained. Results shown in Figure 6 are average of three measurements taken on the wheel path of each of the section evaluated. The value obtained for the 100% manufactured limestone sections between wheel paths (which represent conditions prior to traffic exposure) were double the values shown for the wheel path in Figure 6. The blended sand sections had values much higher than those of the sections made with 100% MFA. DFT60 values increased as the siliceous content (or AI) of the blended sand in the pavement increased.

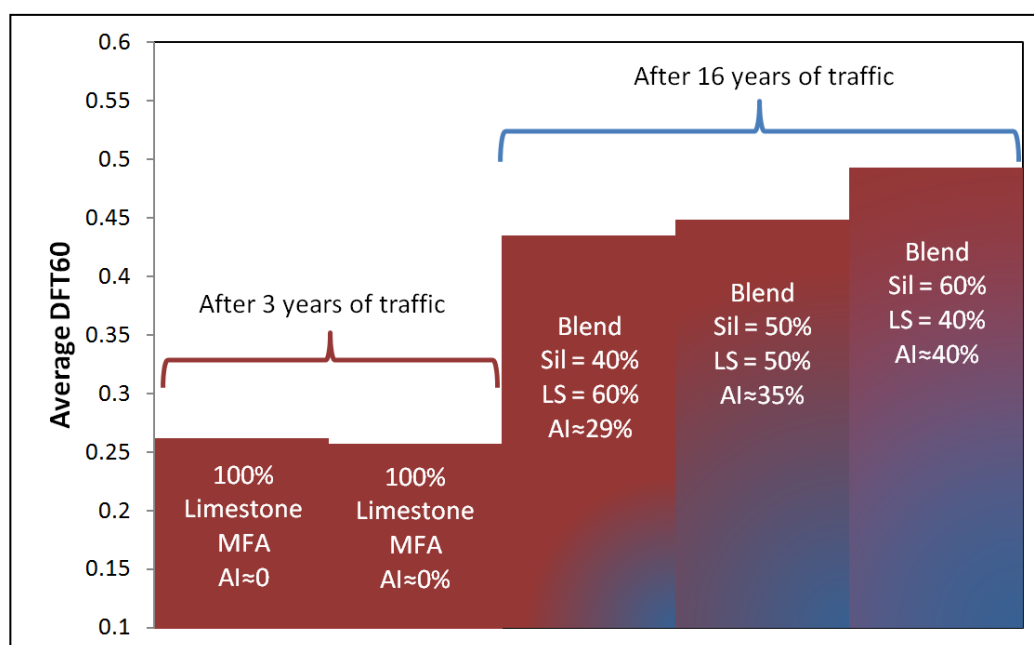


Figure 6. 100% MFA vs. Blended Sands

The values presented in Figure 6 only compared the PCC pavement sections based on the type of sand that was used, and based on the age of the sections. To be able to do a better comparative analysis of those sections it is important to also compare how much traffic each of those sections is exposed to. Although traffic data were not used for the comparison, the data presented in Figure 6 are sufficient to show that there is significant performance difference between PCC pavements made with blended sands and PCC pavements made with 100% manufactured limestone sands.

Laboratory Testing. After 160,000 TWPD polishing cycles, the change in macro-texture (MPD measured by the CTM) was minimal. The friction value obtained from the DFT after 160,000 polishing cycles at 60 km/h (DFT60) was used to compare the performance of the fine aggregates tested (the DFT evaluates the micro-texture). Note that DFT60 and DFT20 are commonly used to compare results obtained using the

DFT. Results for all the sands and blends of sands tested are shown in Figures 7, 8 and 9. The average difference in DFT60 values between two slabs made from the same material at 160,000 cycles was 0.006.

Results presented in Figure 7 show that all the limestone sands tested (except for one) had DFT60 values after 160,000 polishing cycles that were lower than any of the siliceous sands tested. The dolomite sand had a DFT60 value at 160,000 cycles that was comparable to the values obtained with siliceous sands. Unlike the one limestone that performed well, the dolomite was expected to perform better than the other carbonate aggregates. Laboratory results obtained by Balmer and Colley also showed that dolomitic sands had higher wear indices compared to limestone sands [3]. Balmer and Colley's conclusions did not reflect the differences between carbonate sands because they based their conclusions on AI. AI cannot differentiate between carbonate sands since all carbonates sands regardless of their hardness dissolve in acid. No field sections containing the dolomite sand tested could be located (since that sand does not meet AI requirements). It is not clear whether or not dolomite sands would have good performance in the field as they had in the laboratory.

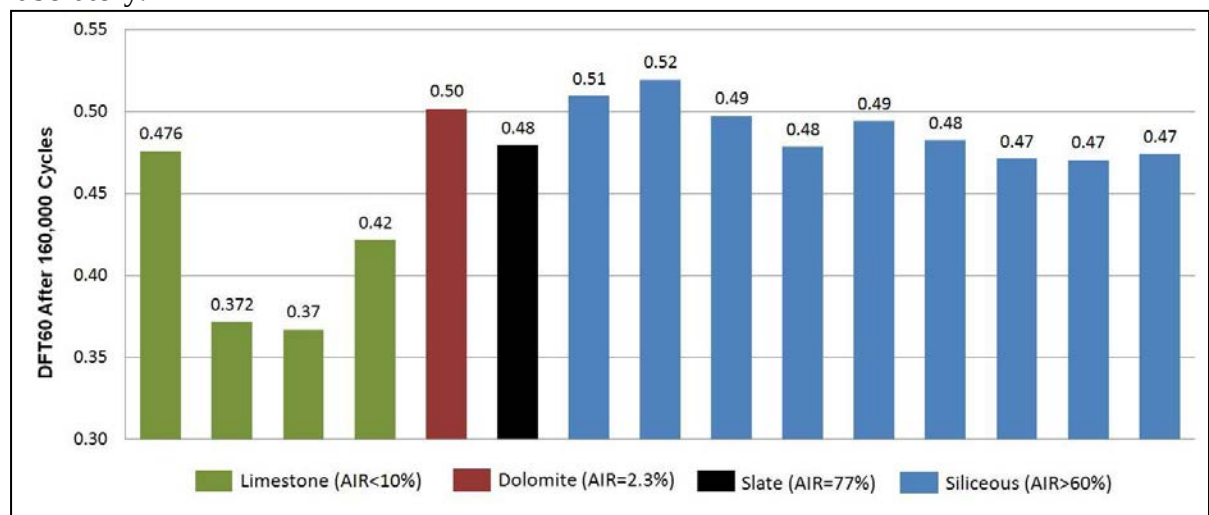


Figure 7. DFT60 Results at 160,000 Cycles for the Different Sands Tested

Combinations of limestone and siliceous sands were blended and tested in concrete. The results presented in Figures 8 and 9 show that even the concrete made with aggregate blends that had an AI of 20% performed considerably better than the concrete made with 100% manufactured limestone sand. Adding a small quantity of siliceous sand had a large effect on friction performance. The results also indicate that increasing siliceous sand content resulted in higher friction values after 160,000 polishing cycles. Those results are also similar to the results obtained by Balmer and Colley [3].

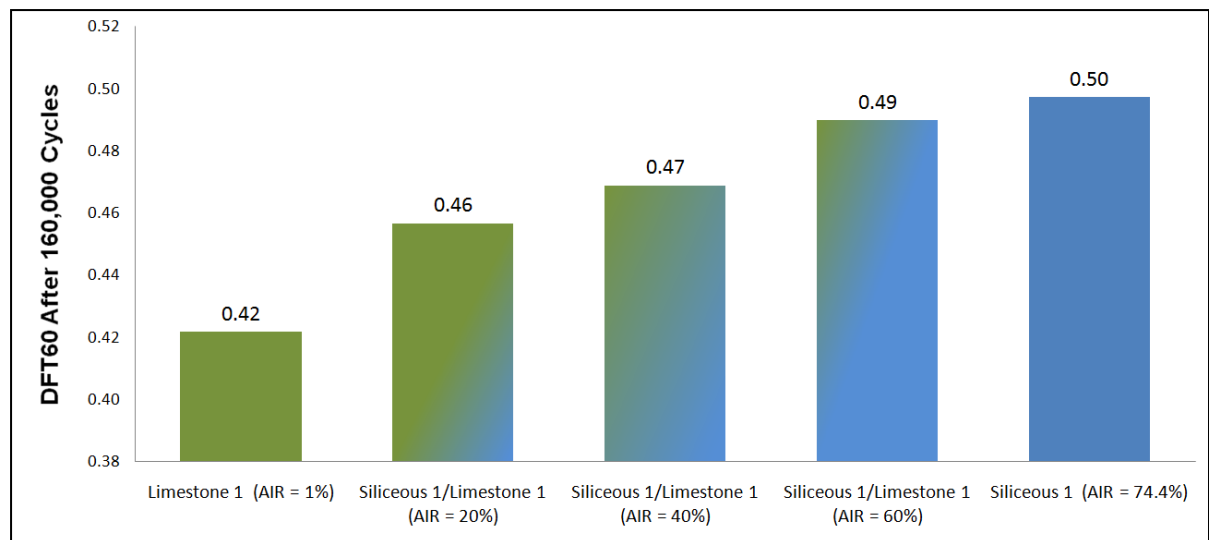


Figure 8. DFT60 Results at 160,000 Cycles for Blended Sands (Siliceous 1 and Limestone 1)

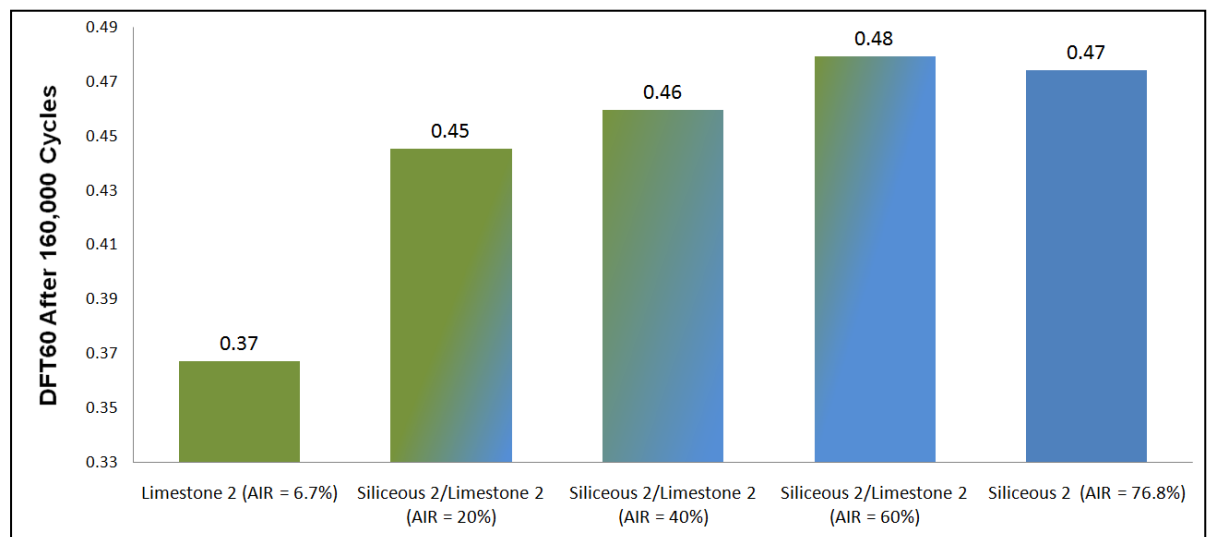


Figure 9. DFT60 Results at 160,000 Cycles for Blended Sands (Siliceous 2 and Limestone 2)

In Figure 10, the results shown in Figures 7, 8 and 9 were compared to the AI values. Except for the carbonate sands, there does seem to be a linear relationship between AI and the friction values obtained for all sands and blends of sands tested. As AI decreased, skid performance decreased for the siliceous sands and the blended sands.

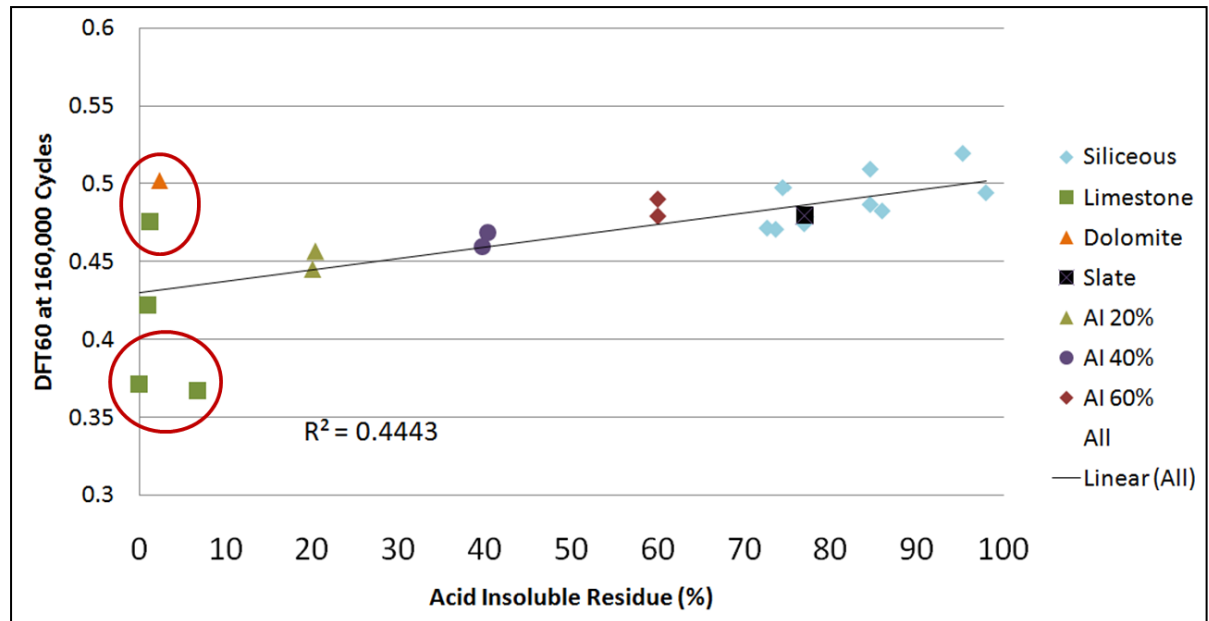


Figure 10. DFT60 at 160,000 Cycles vs. AI (%)

In Figure 11, the results shown in Figures 7, 8 and 9 were compared to micro-Deval percent loss of the sands. Except for one of the limestone sands, the micro-Deval abrasion test seems to better predict the performance of the laboratory concrete specimen tested. In general, very good friction performance can be expected with aggregates (or blends) that have a micro-Deval percent loss less than 12%.

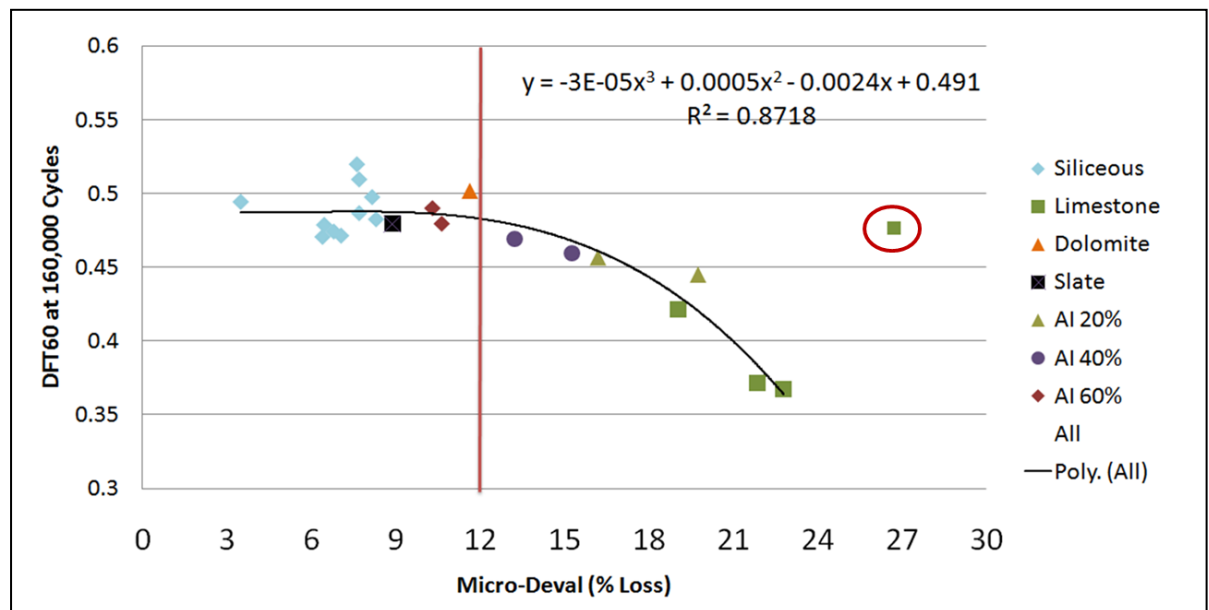


Figure 11. DFT60 at 160,000 Cycles vs. Micro-Deval (%)

Figure 12 shows that there is good correlation between AI values and micro-Deval values for all aggregates except one. The only aggregate that did not perform well in AI but had good micro-Deval performance was the dolomite sand. Dolomites are known to be harder carbonate aggregates, and the reason they fail AI is because they are carbonates and not because they are soft. The 12% micro-Deval limit also seems to correlate well with the 60% AI limit; the only major difference between the

two limits is that if the micro-Deval limit was adopted, it would allow more of the harder carbonate sands to be used (or blends containing higher amounts of manufactured carbonate sands).

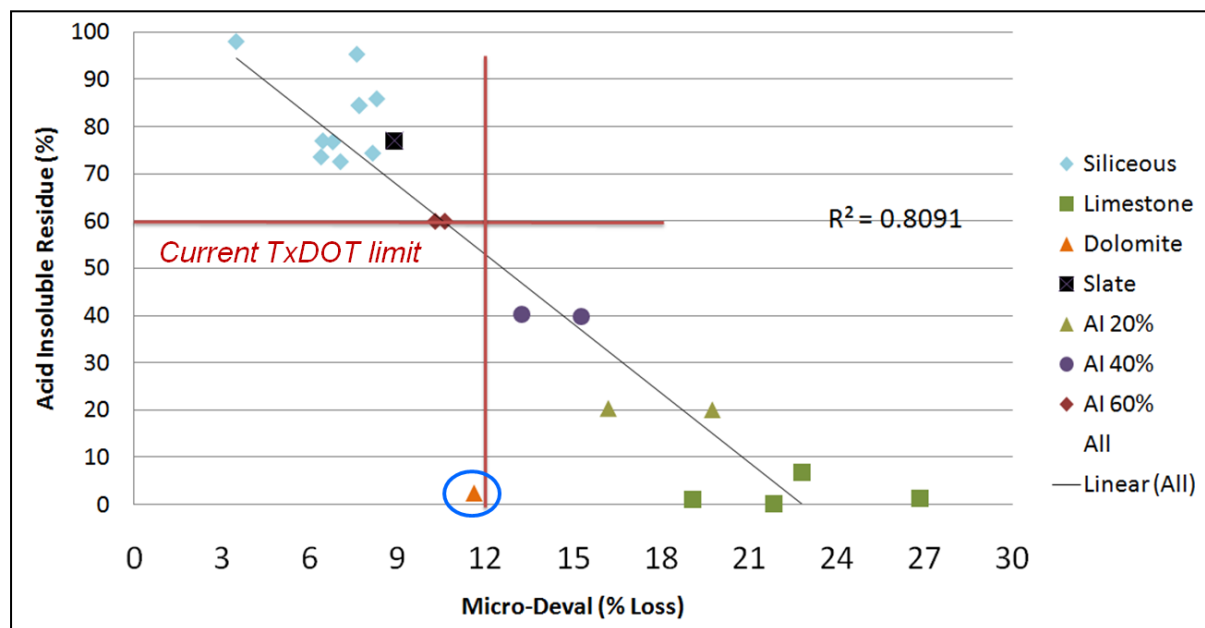


Figure 12. AI (%) vs. Micro-Deval (%)

If blends of the siliceous and limestone aggregates tested during this research project were to be blended to meet a micro-Deval loss of less or equal to 12% ($MD \leq 12\%$), then the minimum AI that can be obtained from such blends would be greater than 40% (Figure 13). A field section containing a blend of aggregates with an AI of 40% was evaluated as part of this project. That section seemed to have maintained good performance after 16 years of service (Figure 6).

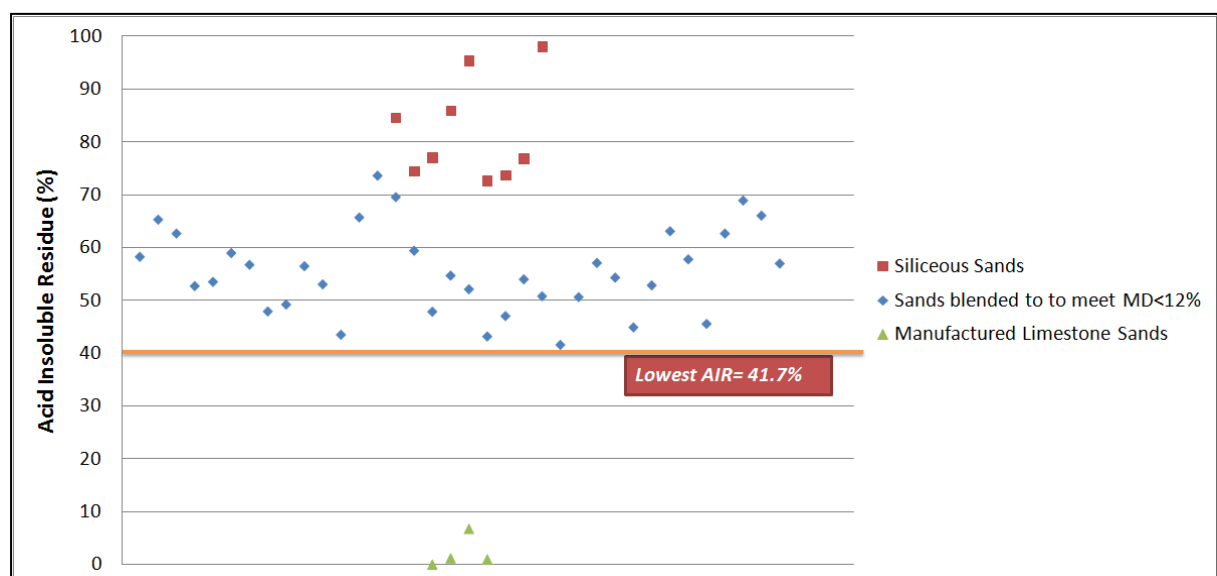


Figure 13. AI Values for Blends of Aggregates Meeting the 12% Micro-Deval Limit

Conclusions

Compared to skid values computed using the IFI formula, DFT60 values were found to better correlate to skid trailer values tested using smooth tires at 80 km/hr for PCC pavements. For that reason DFT60 values were used in this paper to compare the performance of laboratory specimen and field test sections.

Good quality concrete can be produced using MFA if the aggregates are properly evaluated and the right proportions are used. Using 100% limestone sand is not recommended because it might cause early loss of skid resistance. To obtain good skid performance using limestone sands, these sands have to be blended with siliceous sands. For a given sand combination, the higher the siliceous sand content, the better the long-term skid performance.

The acid insoluble residue test used by state agencies is a surrogate test that measures the carbonate content of fine aggregates. Although higher carbonate content might indicate the presence of softer sands, the AI does not directly measure the hardness of the aggregate. The micro-Deval test, on the other hand, is a mechanical test that directly evaluates the hardness by measuring the abrasion resistance of the aggregate. The results obtained in this research indicate that the micro-Deval abrasion test for fine aggregates is more reliable for predicting the performance of concrete tested at the laboratory compared to the AI test. Although only one dolomite sand was tested, dolomitic aggregates are expected to perform better than limestone aggregates. Since dolomite aggregates have not been extensively evaluated in the field, it is hard to recommend using 100% dolomite fine aggregate in concrete paving. However, it would be safe to recommend using more of a harder carbonate aggregate in a blend. Using at least 25% siliceous sand as recommended by Balmer and Colley should not cause early loss in skid resistance, but it will probably not perform as well as a blend containing higher percentage of siliceous sand. Using an AI limit of 60% or a micro-Deval percent loss of 12% should result in good skid performance in PCC pavements.

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