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Preliminary Recommendations for Achieving Adequate Surface Friction in Class P Concrete Containing Manufactured Fine Aggregates

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Chapter 1. Preliminary Recommendations for Achieving Adequate Surface Friction in Class P Concrete Containing Manufactured Fine Aggregates

1.1 Scope

This report summarizes findings and recommendations regarding the usage of manufactured fine aggregates in portland cement concrete pavement (PCCP). The supporting research included both field and laboratory testing of aggregates and concrete properties that relate to skid resistance. Preliminary results show good correlation between friction values obtained using a Dynamic Friction Tester (DFT) and the micro-Deval test for fine aggregates (ASTM D7428). Recommendations on how to blend carbonate sands with low acid insoluble residues are presented in this document.

1.2 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. Since it is difficult to directly measure the resistance of fine aggregate to polishing, other indicator tests have been used. 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 [Folliard and Smith 2003]. 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 45 mph (72 km/h) [Hall et al. 2009].

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 [Balmer and Coley 1966]. After this conference, state agencies started developing equipment to test skid both in the laboratory and in the field [Balmer and Coley]. In 1958, Shupe and Lounsbury showed a correlation between calcium carbonate content of aggregates and skidding susceptibility [Balmer and Coley 1966]. 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 [Balmer and Coley 1966]. 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.

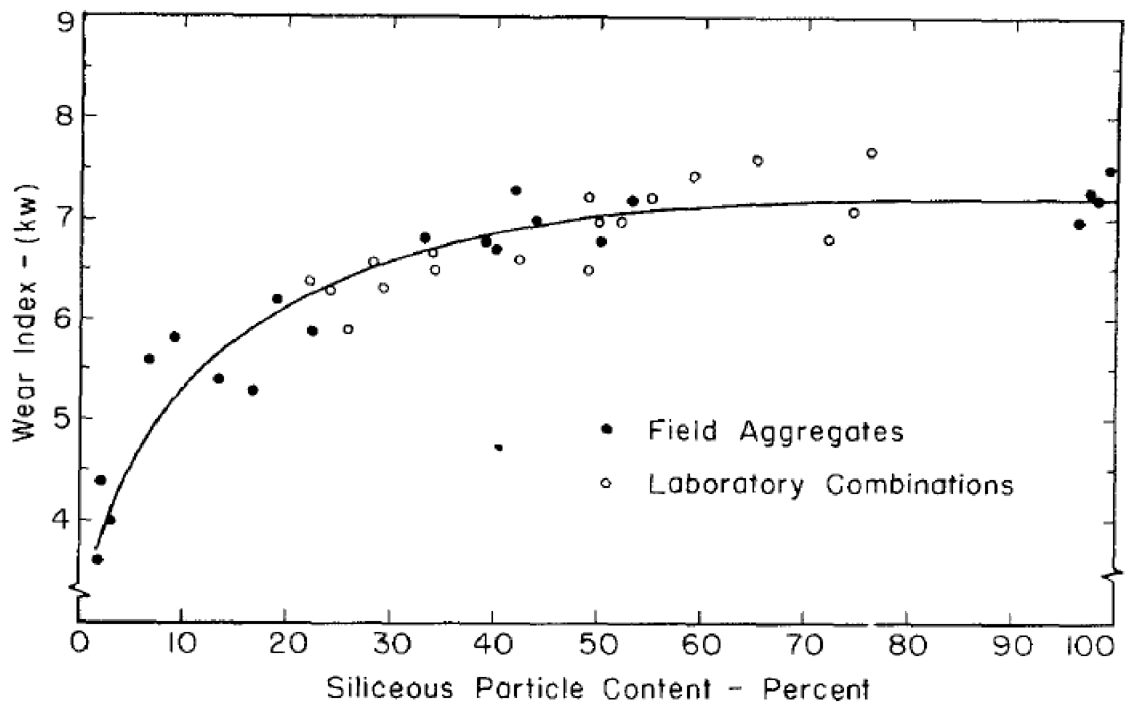

Figure 1.1: Wear Index vs. Siliceous Particle Content (Balmer and Colley, 1966)

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. As part of a study that evaluated micro-texture and macro-texture on PCC pavements in 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.

1.3 Significance and Use

Item 421 of the TxDOT Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges requires that fine aggregates used in Class P Concrete meet a minimum acid insoluble residue (AI) limit of 60%. The AI test (Tex-612-J) indirectly evaluates the hardness of fine aggregates by assessing the presence of noncarbonated material. Since a more concentrated hydrochloric acid is used in the TxDOT test, all carbonate aggregates fail the AI test.

Districts in Texas, such as Dallas and Fort Worth, do not have sufficient sources of fine aggregates that meet the AI requirements. In order to meet an AI of 60%, the Dallas and Fort Worth Districts have to haul aggregates from distant pits and blend them with their local sources. The concern with using fine aggregates that do not meet AI limits is that those aggregates might result in poor skid performance. If more local carbonaceous aggregates are to be used in PCC pavements, it is important to investigate whether or not AI values for fine aggregates accurately relate to or predict the skid performance of PCC pavements.

An alternative method of evaluating and blending fine aggregates for pavement concrete is presented at the end of this document. This method aims at better quantifying the hardness of aggregates through their resistance to abrasion and crushing rather than their resistance to acid.

1.4 Test Methods to Evaluate Aggregates and Estimate Concrete Surface Skid Performance

Aggregates were tested for AI using the test described in Tex-612-J. The micro-Deval (MD) test described in ASTM D 7428 was used to evaluate the resistance of fine aggregates to abrasion and crushing. Although TxDOT uses Tex-461-A to evaluate coarse aggregates by MD, there is no state method to evaluate fine aggregates by MD.

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 40 mph (64 km/h) or 50 mph (80 km/h). 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.

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. The 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 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.

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 [7]. 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 50 mph using a smooth tire, the following equations can be used:

$$SN(50)_{smooth} = \left(\frac{F60-0.045}{0.925} \times \frac{1}{e^{\frac{20.47}{S_P}}}\right) \times 100 \qquad \text{(eq. 1)}$$

$$F60 = 0.082 + 0.732 DFT_{20} e^{-40/S_p} \qquad \text{(eq. 2)}$$

$$S_P = 14.2 + 89.7 MPD \qquad \text{(eq. 3)}$$

where $F60$ and S_p are the International Friction Index (IFI) parameters, DFT_{20} is the coefficient of friction at 20 km/hr obtained from the DFT, ***MPD*** is the texture reading measured using the CTM, and $SN(50)_{smooth}$ is the calculated skid number at 50 miles/hour using a smooth tire.

$SN(50)_{smooth}$ was calculated and compared for the field data only. For the laboratory testing the values of the DFT_{60} were compared. The reason this was done is because the goal of the lab test is to evaluate fine aggregates prone to polishing. The CTM measures macro-texture (wavelength of 0.02 in. to 2 in.), while the DFT evaluates micro-texture (wavelength < 0.02 in.). Since the texture created by the presence of fine aggregates fits more in the micro-texture range, the DFT values are able to better evaluate the polishing of fine aggregates. DFT_{60} was chosen instead of DFT_{20} because research done by the National Center for Asphalt Technology (NCAT) (Figure 1.2) shows that DFT_{60} correlates well with locked wheel skid trailer values using ribbed tires (ASTM E 501). Using ribbed tires in a skid trailer is a better way of evaluating micro-texture (smooth tire values represent the combined effect of micro-texture and macro-texture).

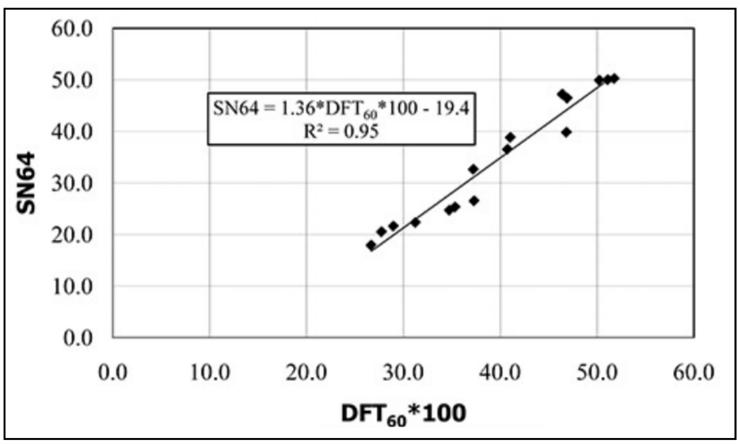

Figure 1.2: Correlation between $\mathbf{SN(64)_{ribbed}}$ and $\mathbf{DFT_{60}}$ (metric units) [6]

1.5 Field Evaluation

Two sites in the Fort Worth area were evaluated. The first was constructed in 2008 on Business 287 near Saginaw. The Saginaw sections consisted of four sections, three of which were made with 100% manufactured limestone aggregate having different microfine contents (aggregate passing the No. 200 sieve). The other site is located on SH 101 in Wise County north of US 380 near Bridgeport. The Bridgeport site consists of three sections constructed in 1995 using blends of sands that did not meet the 60% AI limit.

Sections 1 and 2 at Saginaw were constructed using 100% manufactured limestone aggregate on the outside lane. Section 1 had 5% microfine content while section 2 had 10%.

Section 3 was also constructed using 100% carbonate aggregate but had 15% microfines—section 3 was constructed on the inside lane, thus exposed to different traffic. A 50/50 blend of siliceous and carbonate aggregate blend was used for section 4, also on the inside lane.

The skid number $\boldsymbol{SN(50)_{smooth}}$ of sections 1 and 2 (Figure 1.3) was approximately 10 (on the wheel path), while $\boldsymbol{SN(50)_{smooth}}$ for sections 3 and 4 was significantly higher. Those results were expected because the inside lane (sections 3 and 4) is exposed to different traffic (the outside lane sees more truck traffic). Section 3 had lower $\boldsymbol{SN(50)_{smooth}}$ values on the wheel path compared to section 4.

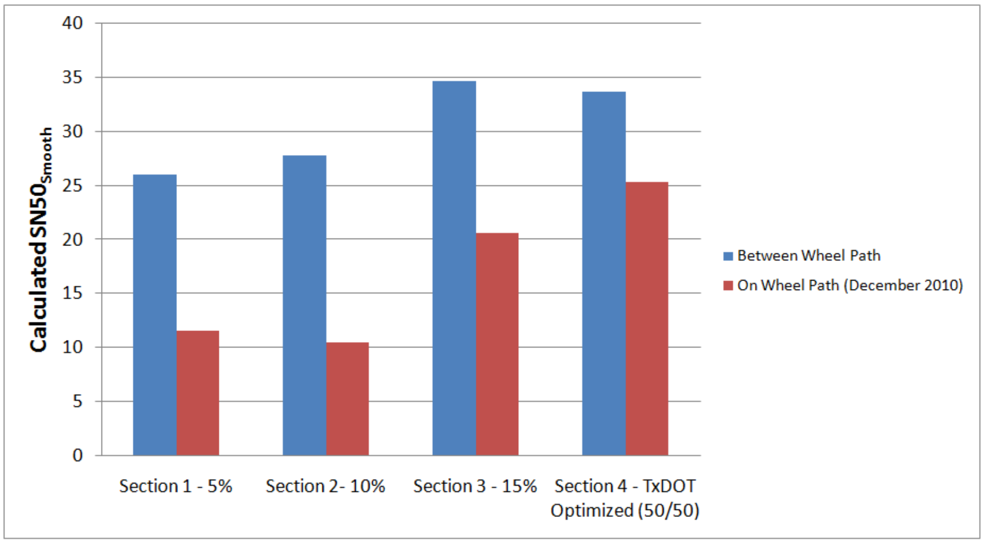

Figure 1.3: Computed $\mathbf{SN(50)_{smooth}}$ for Saginaw Sections after 2 years of Traffic

Comparing $\boldsymbol{DFT_{60}}$ values provides a good indication of the contribution of the micro-texture in skid resistance. Low $\boldsymbol{DFT_{60}}$ values indicate a higher degree of polish of fine aggregates. Compared to sections 3 and 4, sections 1 and 2 had lower $\boldsymbol{DFT_{60}}$ values (Figure 1.4) since these two sections received more traffic in the outside lanes.

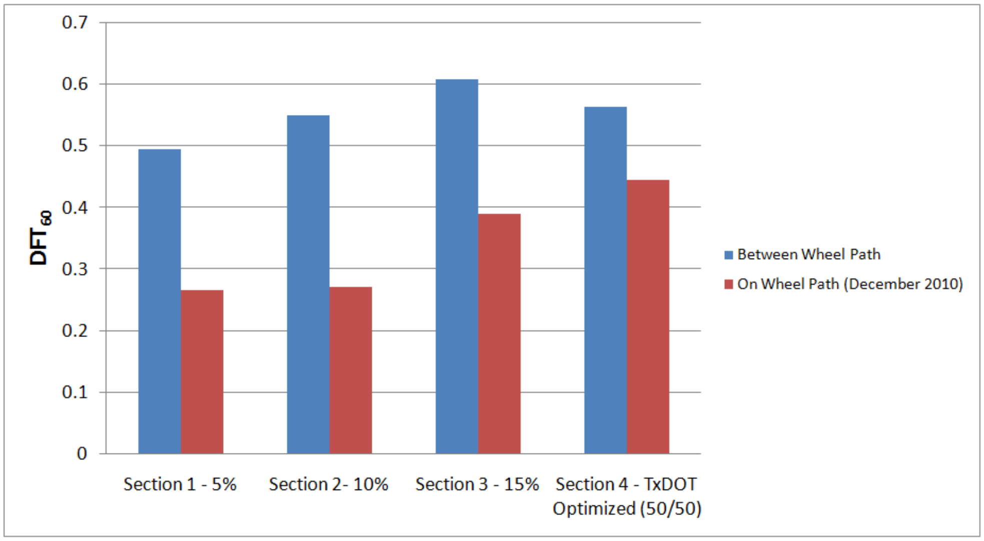

Figure 1.4: **DFT$_{60}$** for Saginaw Sections after 2 years of Traffic

It should be noted, however, that significant workability and finishability problems were encountered during the construction of sections 1, 2, and 3. The surface of those three sections was excessively sprayed with water to enable the finishers to finish the surface of the pavement. It is still unclear how much excessively spraying the surface with water affected the performance of those the sections made with 100% manufactured limestone fine aggregate.

The Bridgeport sections were constructed on the inside lane of a highway mainly used by trucks transporting aggregates (the sections are subject to a high percentage of truck traffic). The following blends of fine aggregates were used for these sections:

- A 60/40 TXI Paradise (siliceous)/TXI Bridgeport (limestone) blend (AI = 40%)
- A 50/50 TXI Paradise (siliceous)/TXI Bridgeport (limestone) blend (AI = 35%)
- A 40/60 TXI Paradise (siliceous)/TXI Bridgeport (limestone) blend (AI = 29%)

The ***SN(50)$_{smooth}$*** value on the wheel path for the 60/40 blend is the highest (Figure 1.5). Even though the Bridgeport sections have been in service for 15 years and the Saginaw sections have only been in service for 2 years, the ***SN(50)$_{smooth}$*** values in the wheel path for all the Bridgeport sections are almost twice as high as those in the wheel path obtained from sections 1 and 2 at Saginaw (Figures 1.3 and 1.5).

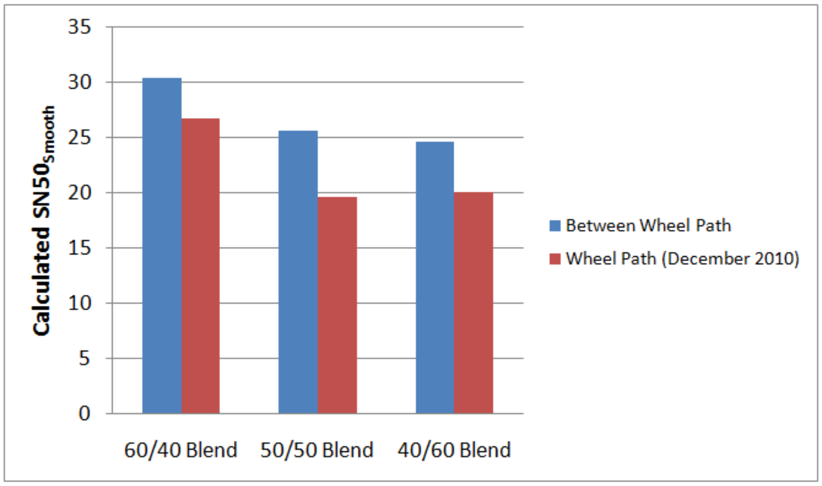

Figure 1.5: Computed $\mathbf{SN(50)_{smooth}}$ for Bridgeport Sections after 15 years of Traffic

The $\boldsymbol{DFT_{60}}$ values for the 60/40 blend sections were higher than the $\boldsymbol{DFT_{60}}$ values for sections containing the 50/50 blend and the 40/60 blend (Figure 1.6). This indicates that the micro-texture of the 60/40 blended sections is less polished. The DFT values of the blended sections at Bridgeport are also significantly higher than the $\boldsymbol{DFT_{60}}$ of sections 1 and 2 at Saginaw (Figures 1.4 and 1.6).

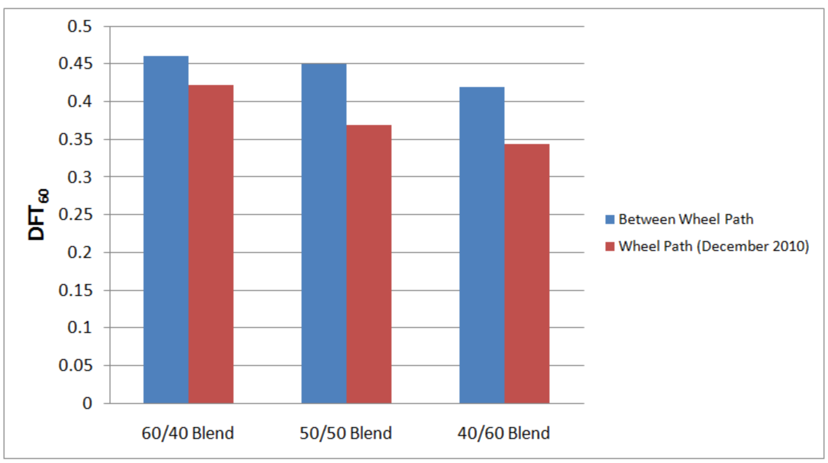

Figure 1.6: $\mathbf{DFT_{60}}$ for Bridgeport Sections after 15 years of Traffic

By comparing the results of the Bridgeport and Saginaw sections, it can be concluded that using a 100% manufactured limestone fine aggregate likely resulted in more loss of skid resistance than when some siliceous sand is present. Blending a limestone aggregate with a small percentage of siliceous fine aggregate can have a high impact on skid performance. Skid performance seems to increase as a result of using blends of aggregates with higher siliceous content.

1.6 Laboratory Testing

The goal of the laboratory testing was to evaluate the polish resistance of concrete slabs made with different fine aggregates and to relate those results to aggregate tests. The CTM and DFT were used along with a three-wheel polishing device (TWPD) to evaluate the polish resistance of a laboratory concrete specimen. The TWPD simulates the wear caused by traffic. The wheels used on the TWPD were hard polyurethane casters loaded to exert an average stress of 50 psi on the concrete specimen. For each sand or blend of sands two slabs were tested. The volumetric mixture proportions for all tested specimens were the same.

In Figure 1.7, results of $\boldsymbol{DFT_{60}}$ after 160,000 polishing cycles on concrete specimens are compared to the AI values of aggregate used. Figure 1.7 shows that some of the carbonate aggregates that had low AI performed as well as the aggregates that had a high AI. There does seem to be a relation between AI and the performance of siliceous and blended aggregates; as the AI decreases, $\boldsymbol{DFT_{60}}$ values after 160,000 cycles decrease for siliceous and blended aggregates. The relation between AI and $\boldsymbol{DFT_{60}}$ values for carbonate aggregates (limestone or dolomite) is not clear. Two of the aggregates that failed AI did not reach a low $\boldsymbol{DFT_{60}}$ value after 160,000 polishing cycles.

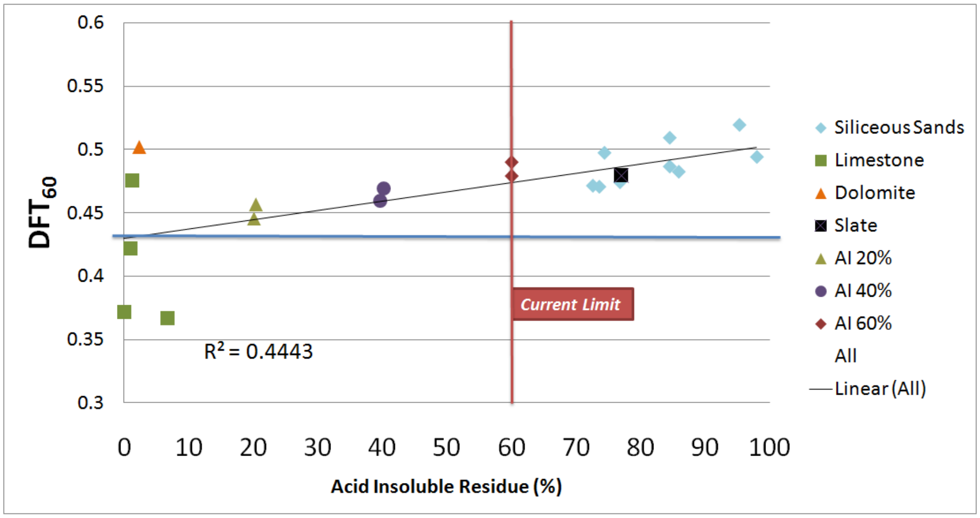

Figure 1.7: $\mathbf{DFT_{60}}$ after 160,000 TWPD cycles vs. AI

An alternative way of evaluating aggregates for polish resistance was considered for the laboratory testing. Fine aggregates were tested using the MD test (ASTM D 7428). Values of AI and MD are compared in Figure 1.8.

There is good correlation between the AI test and the MD test. The only fine aggregate that performs well in MD but fails AI is the dolomitic aggregate. That same aggregate had a $\boldsymbol{DFT_{60}}$ after 160,000 TWPD cycles comparable to the values obtained with siliceous sands.

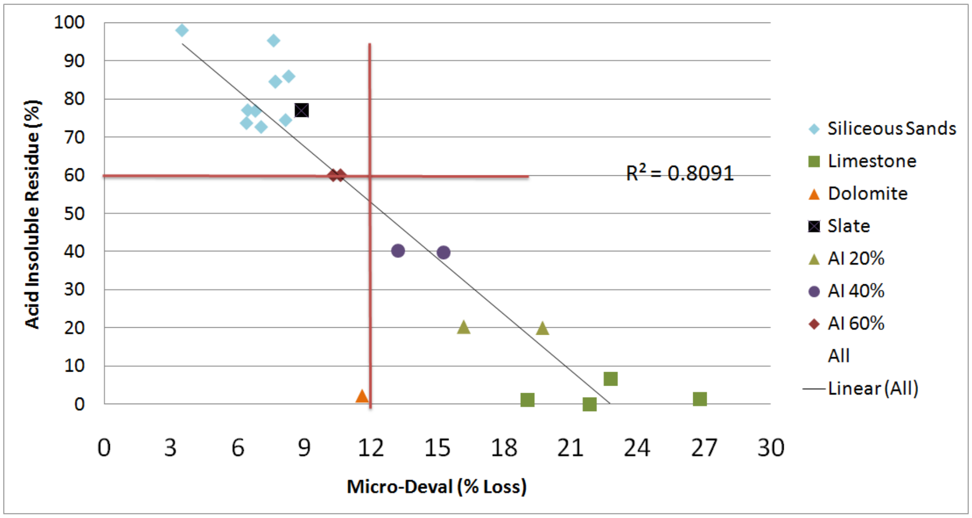

Figure 1.8: AI vs. MD

Dolomites are known to be harder carbonate aggregates, and the reason they fail AI is only because of their chemistry and not because of their hardness. It should be noted that the AI test is only a surrogate test for evaluating the polish resistance of fine aggregates in PCCP, and the test was originally developed based on an observation that an increase in non-carbonate content improves skid resistance (Balmer and Colley). The concrete test results obtained by Balmer and Colley in 1966 also seem to indicate that dolomites perform better than limestone fine aggregates (note limestones are referred to as calcites in this paper – Figure 1.9)

Fine Aggregate No.	Principal Constituents, %	Rating of Field Performance	Wear Index, kw
1......	90 calcite	poor	3.6
2......	70 calcite 24 dolomite	poor	4.4
3......	90 calcite	poor	4.0
4......	80 dolomite	poor	5.6
5......	75 dolomite	poor	5.8
6......	70 dolomite	poor	5.4
7......	60 calcite 16 silt and clay	poor	5.3
8......	80 calcite 15 quartz	fair	6.2
9......	65 calcite 12 dolomite	poor	5.9
10......	50 calcite 33 mica and quartz	excellent	6.8
11......	55 dolomite 39 quartz, quartzite, and feldspar	excellent	6.8
12......	55 calcite and dolomite 40 quartz, mica, and epidote	excellent	6.7
13......	45 calcite 42 quartz and feldspar	excellent	7.3
14......	50 dolomite 44 quartz	excellent	7.0
15......	45 dolomite 45 quartz	excellent	6.8
16......	45 dolomite 45 quartz	excellent	7.2
17......	30 graywacke 55 quartz	excellent	7.0
18......	75 quartz 17 feldspar	excellent	7.3
19......	72 quartz 20 feldspar	excellent	7.2
20......	99 quartz	excellent	7.5

Figure 1.9: AI vs. MD

Figure 1.10 shows the relation between $\boldsymbol{DFT_{60}}$ after 160,000 TWPD cycles and MD. Except for one of the limestone sands, which are all at or near zero on the AI scale, the MD test seems to have good correlation with $\boldsymbol{DFT_{60}}$. Note that some research has indicated that higher content of shale or chert in an aggregate sample could lead to higher micro-Deval percent loss [Hudec and Boateng 1995].

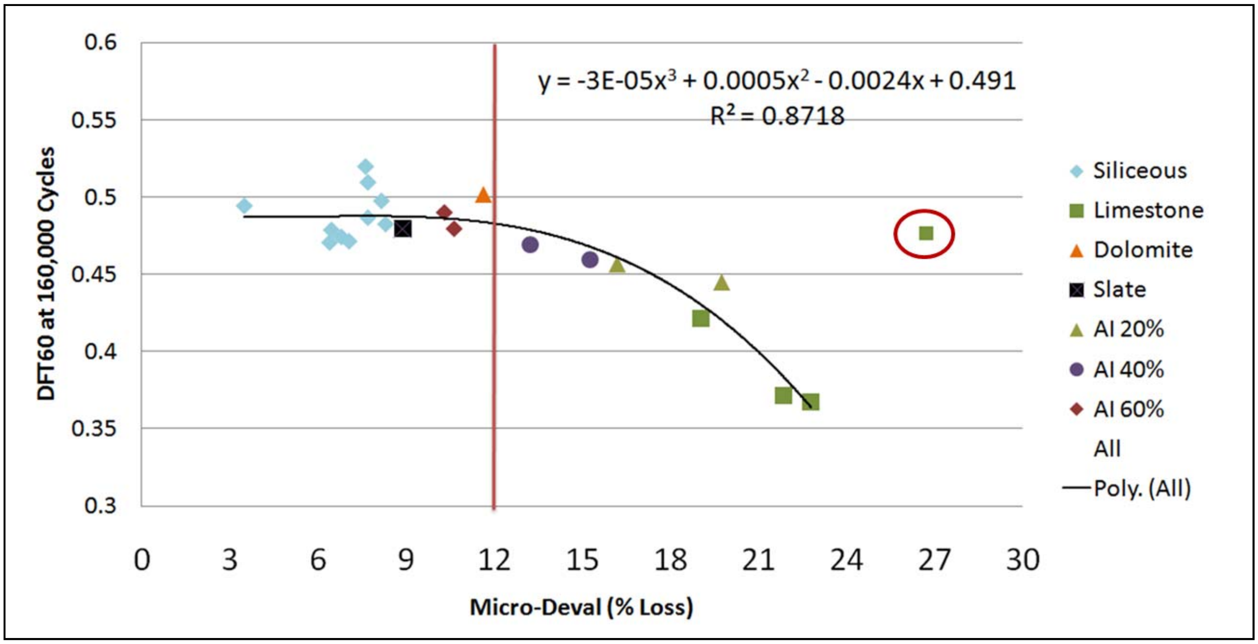

Figure 1.10: **DFT_{60}** after 160,000 TWPD cycles vs. MD

1.7 Recommendations

The following method is recommended as an alternative preliminary procedure for accepting and blending aggregates for class P concrete:

1) Test unblended fine aggregate(s) using Tex-612-J (acid insoluble residue).
   a) If AI ≥ 60%, no need for further testing of fine aggregates for polish resistance.
   b) If AI < 60%, further testing of fine aggregates is needed.
2) Test fine aggregates using the micro-Deval (MD) test (ASTM D 7428).
   a) If the micro-Deval percent loss of a fine aggregate is less than 12% (MD < 12%), blend this fine aggregate with at least 40% of a fine aggregate that has an AI ≥ 60%.
   b) If the micro-Deval percent loss of a fine aggregate is greater than 12% (MD ≥ 12%), then blend this fine aggregate such that the equivalent micro-Deval percent loss of the combined fine aggregate is less than 12% (MD < 12%):

$$[(\%Agg1) \times (\%loss\ of\ Agg1)] \times [(\%Agg2) \times (\%loss\ of\ Agg2)] < 12\%$$

Note that all aggregates have to be tested prior to blending. Aggregate test values obtained from testing blended fine aggregates using Tex-612-J and ASTM D 7428 should not be used to identify polish resistant aggregates in PCCP.

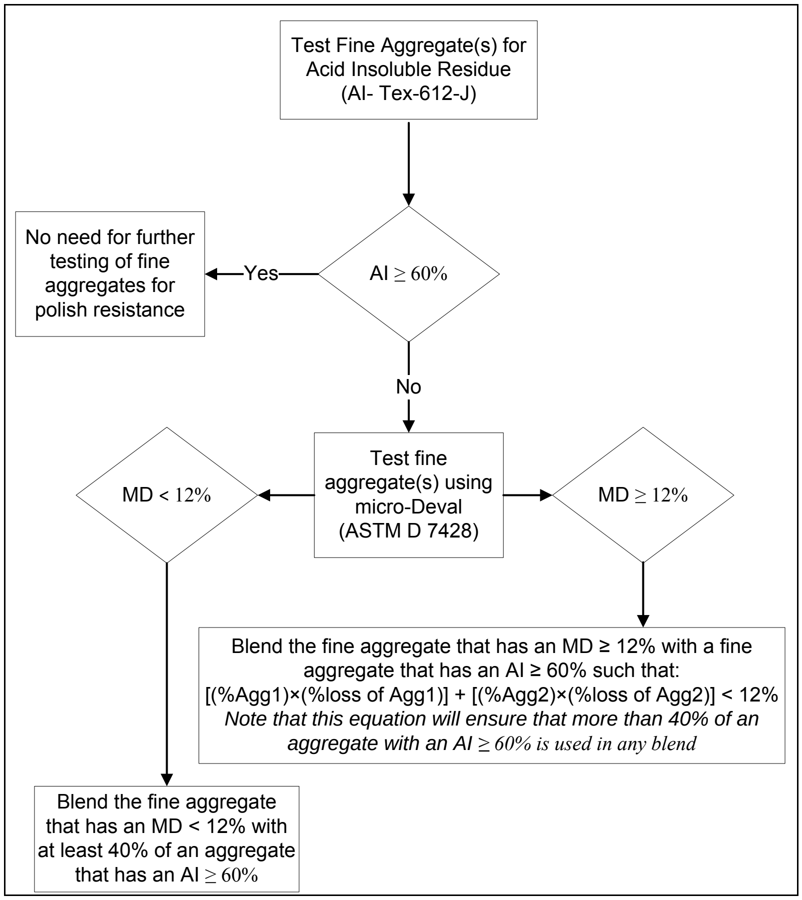

Figure 1.11: Testing Polish Resistance of Fine Aggregates in PCCP

If this method of blending is used instead of the current specifications, then more manufactured carbonate sand will be allowed in pavements if the manufactured sand itself is hard, or if it is blended with harder siliceous sands (hardness is evaluated by the MD test).

If blends of the siliceous and limestone aggregate tested during this research project were to be blended to meet a MD loss of less 12%, then the minimum AI that can be obtained from such blends will be greater than 40% (Figure 1.12).

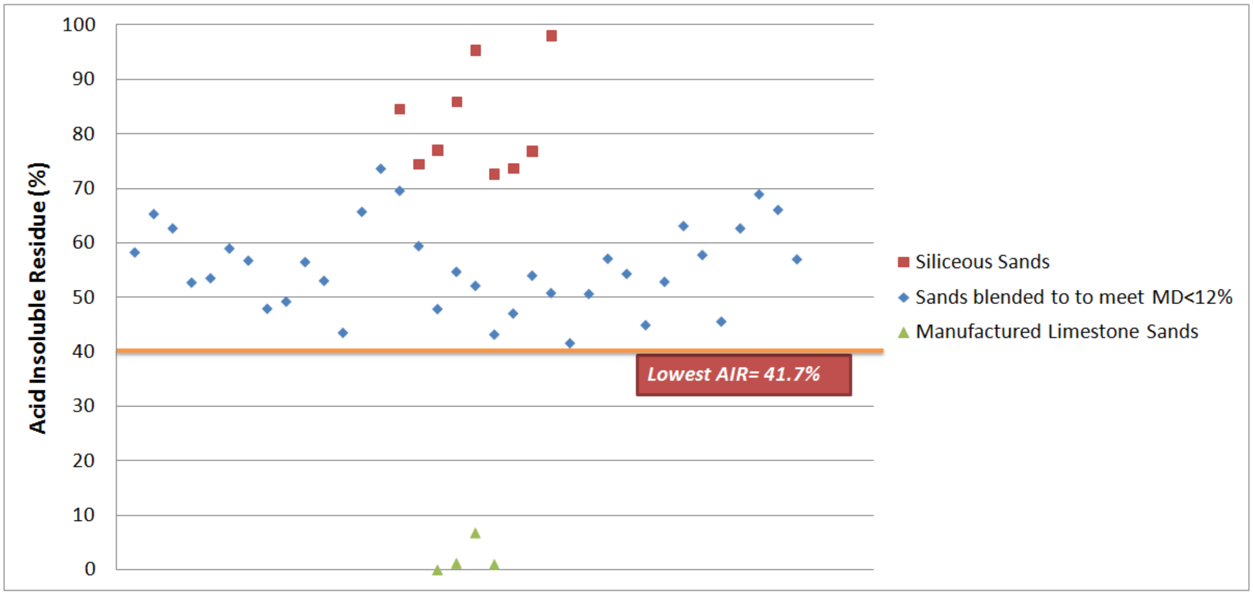

Figure 1.12: AI Values for Blends of Aggregates Meeting the 12% MD Limit

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