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Maximizing the Use of Local Materials in HMA Surfaces

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MAXIMIZING THE USE OF LOCAL MATERIALS IN HMA SURFACES

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One approach to reducing initial construction costs is to maximize the use of locally available aggregates. The main concern with using locally available carbonate aggregates, however, is that they tend to polish under traffic and provide inadequate friction. INDOT specifications for asphalt surface mixes, especially for high volume traffic, require high friction aggregates like steel slag, blast furnace slag or sandstone, which are more resistant to polishing. These premium aggregates are not readily available in all parts of the state, requiring long haul distances from limited sources in Indiana or out of state.

The study summarized here was conducted to investigate the feasibility of using greater quantities of local, less polish resistant aggregates, specifically limestones, in asphalt surfaces when blended with high friction aggregates.

Samples of blends of various quantities of polish-susceptible aggregates with high friction aggregates were prepared, polished to simulate the action of traffic, and tested in the laboratory for their frictional properties. The variables considered include mix type (HMA and SMA), coarse aggregate type (two polish-susceptible aggregates blended with steel furnace slag, blast furnace slag and sandstone), polish-susceptible aggregate content, and amount of limestone fine aggregate (in HMA).

The results of this study demonstrate that local, polish susceptible aggregates can be used to replace the high quality friction aggregates in HMA and SMA surface mixtures without detrimental effect on friction.

In addition, the laboratory evaluation procedures used in this study could be implemented as a screening test for new materials or new types of mixtures. Such a screening test would allow contractors, material suppliers and INDOT to ascertain whether a material warrants further investigation before the effort and funds are invested in construction of a field trial.

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EXECUTIVE SUMMARY

MAXIMIZING THE USE OF LOCAL MATERIALS IN HMA SURFACES

Introduction

Like most other highway agencies in today's economy, the Indiana Department of Transportation (INDOT) needs to search for ways to reduce construction costs. One approach to this issue is to maximize the use of locally available materials, specifically local aggregates. INDOT specifications already allow widespread use of local aggregates in deeper courses of hot mix asphalt (HMA) pavements, but surface mixes (especially for high volume traffic) typically require high friction aggregates such as steel slag, blast furnace slag or sandstone for safety. These types of aggregates are not readily available in all parts of the state, requiring long haul distances from limited sources in Indiana or even out of state. These premium aggregates are more expensive plus have the additional cost of transportation.

The main concern with using local materials is pavement friction. Most efforts to control HMA surface friction are based on specifying and/or testing the aggregate. For example, INDOT's standard specifications allow only certain aggregate types to be used in HMA and Stone Matrix Asphalt (SMA) surfaces depending on the expected traffic level. HMA surfaces for high volume roadways may include either air cooled blast furnace slag (ACBF), steel furnace slag (SF) or sandstone (SS). Other coarse aggregates may be used if they are demonstrated to be "polish resistant" according to Indiana Test Method (ITM) 214. Steel furnace slag and sandstone are allowed for SMA surfaces regardless of traffic level; crushed dolomite and polish resistant aggregates (PRA) may be used if blended with sandstone or steel slag.

The study summarized here was conducted to investigate the feasibility of using greater quantities of local, less polish resistant aggregates, specifically limestones, in asphalt surfaces. Samples of blends of various quantities of polish susceptible aggregates with high friction aggregates were prepared, polished to simulate the action of traffic, and tested in the laboratory for their frictional properties. The variables considered include mix type (HMA and SMA), coarse aggregate type (two polish susceptible aggregates blended with steel furnace slag, blast furnace slag and sandstone), polish susceptible aggregate content, and amount of limestone fine aggregate (in HMA).

Findings

In short, the evaluation of various blends of coarse aggregates showed that adding local, polish susceptible coarse aggregate to a mix with high quality friction aggregates does cause a decrease in friction. As the amount of local aggregate increases, the friction decreases. Some local aggregate, however, can be added and still produce a mixture with adequate frictional properties. The amount of local coarse aggregate that can be added and still provide adequate friction varied between 20% and 30%. As the amount of local aggregate increased, however, the friction values began to approach the estimated friction flag value of about 0.20. In SMA mixes, perhaps higher amounts of local aggregate could be used from a frictional point of view, but there are other considerations, such as particle strength, that may limit aggregate choices.

In the evaluation of fine aggregate, there were some testing issues that may reduce the reliability of the results. Specifically, the mixes seem to show excessive changes in the surface texture during polishing. It is not clear if this is related to the specimen fabrication or if these mixes are more sensitive to the shearing action of the tires on the polishing machine. This should be studied in future research. Given that caveat, however, the results generally show that adding a small amount of local fine aggregate may reduce the friction level. If the amount of local fine aggregate is limited and high quality coarse aggregate is used, the friction level may still be adequate.

This study evaluated only one size of mix, 9.5 mm. Previous research has shown that larger nominal aggregate size mixes may provide higher friction levels. There is also evidence that smaller nominal aggregate size mixes may require higher frictional quality aggregates, in part at least, because of their reduced macrotexture. Extension of these findings and recommendations to other mix sizes should be done cautiously, and preferably should be guided by additional research in the lab and/or field.

Another previous study evaluated the potential effects of poor quality aggregate in reclaimed asphalt pavement (RAP) if the RAP is reused in high volume surface mixes. The final report on that project suggests that up to 20%–25% poor frictional quality RAP could be used in surface mixes without detrimental effect on the friction level. The possible allowable local aggregate levels recommended in this study are in substantial agreement with that other study. This is reasonable since once in the mix, the aggregate behaves the same whether it came from RAP or was virgin aggregate, at least in terms of friction.

The laboratory techniques used in this study are definitely useful since trial mixes or new materials can be evaluated without risk to the public. Additional refinement is recommended, however, to develop them more fully and address some of the problems noted in this study. Particularly, there is a need to examine the compaction process, equipment calibration and data interpretation. Further comparisons of the lab and field measured friction levels to further refine the friction flag value would also be extremely useful. The procedures could then be used as a screening test to approve new aggregates or mix types for field trials, similar to the approach in the current ITM 214.

Implementation

The results of this study demonstrate that local, polish susceptible aggregates can be used to replace a portion of high quality friction aggregates in HMA and SMA surface mixtures without detrimental effect on friction. Replacing some of the premium materials with locally available aggregates will help to reduce costs while maintaining safety. In addition to reduced material costs (by using less of the "premium" high quality aggregates), hauling costs and energy consumption will also be reduced by using more materials from the local area.

Based on the results of this study, an allowable threshold of 20% local coarse aggregate and 20% local fine aggregate could be allowed for high volume surface mixes when blended with high quality friction aggregates, namely steel furnace slag, air cooled blast furnace slag or sandstone. This finding could be implemented by revising section 904.03 of the standard specifications.

In addition, the laboratory evaluation procedures used in this study could be implemented as a screening test for new materials or new types of mixtures. An ITM could be written similar to ITM 214 to evaluate whether new materials should be placed in field trial sections. Such a screening test would allow contractors, material suppliers and INDOT to ascertain whether a material warrants further investigation before the effort and funds are invested in construction of a field trial.

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1. INTRODUCTION

Like most other highway agencies in today's economy, INDOT needs to search for ways to reduce construction costs. One approach to this issue is to maximize the use of locally available materials, specifically local aggregates. INDOT specifications already allow widespread use of local aggregates in deeper courses of hot mix asphalt (HMA) pavements, but surface mixes (especially for high volume traffic) typically require high friction aggregates such as steel slag, blast furnace slag or sandstone for safety. These types of aggregates are not readily available in all parts of the state, requiring long haul distances from limited sources in Indiana or even out of state. These premium aggregates are more expensive plus have the additional cost of transportation.

The main concern with using local materials is pavement friction. The coarse aggregate portion of an HMA mix plays a large role in providing the surface friction; therefore most efforts to control HMA surface friction are based on specifying and/or testing the coarse aggregate. For example, INDOT's standard specifications allow only certain aggregate types to be used in HMA and Stone Matrix Asphalt (SMA) surfaces depending on the expected traffic level. HMA surfaces for high volume roadways may include either air cooled blast furnace slag (ACBF), steel furnace slag (SF) or sandstone (SS). Other coarse aggregates may be used if they are demonstrated to be "polish resistant" according to Indiana Test Method (ITM) 214 *(1)*. Steel furnace slag and sandstone are allowed for SMA surfaces regardless of traffic level; crushed dolomite and polish resistant aggregates (PRA) may be used if blended with sandstone or steel slag.

As the literature review in Appendix A shows, however, the coarse aggregate alone does not determine the pavement friction. The fine aggregate and overall mix design also contribute to the friction level. In fact, the INDOT specifications do address the fine aggregate fraction. While there is essentially no limit on the types of fine aggregate that can be used in an SMA, crushed limestone fine aggregate is limited to no more than 20% by weight of the total aggregate for HMA surfaces with over 3 million ESALs. (SMAs typically include relatively low amounts of fine aggregate and use a very high quality coarse aggregate, so the contribution of the fine aggregate fraction would likely be minimal.)

These limits on aggregate types and contents are, to a great extent, based on historical frictional performance. The specified aggregates were used in HMA mixes and their performance was monitored over time. A 1995 JTRP study *(2)* led to the development of ITM 214 *(1)* to open the door to use of coarse aggregates that did not have this performance history, provided they performed well in a laboratory test and a short-term field trial (one to two years).

The study summarized here was conducted to investigate the feasibility of using greater quantities of local, less polish resistant aggregates—both coarse and fine—in asphalt surfaces.

2. PROBLEM STATEMENT

INDOT, like other states, needs to reduce construction costs. One means of reducing costs is to reduce the material cost and haul distances for aggregates used in HMA construction. However, locally available aggregates may not provide the required levels of friction needed to ensure safety on wet pavements. Blending local materials with high friction aggregates has proven successful in the past, but in today's economic climate with volatile fuel prices, it would be beneficial to use higher quantities of local materials to reduce costs even further. This study explored whether INDOT could allow higher percentages of locally available, polish susceptible aggregates in HMA surfaces without reducing the overall frictional properties of the pavement.

3. OBJECTIVES

The objectives of this project were to determine:

- If higher percentages of polish susceptible aggregates—both fine and coarse—can be allowed in HMA surfaces without affecting the overall pavement quality.
- If so, what is the maximum amount of polish susceptible aggregates that can be allowed?

4. FINDINGS AND DELIVERABLES

The issue of using local aggregates for surface mixes is essentially a question of friction. Many of the locally available aggregates are predominantly carbonates and may be susceptible to polishing under traffic. (Hence, the terms local aggregate and polish susceptible aggregate are used interchangeably in this report.) This study explored whether a certain level of polish susceptible aggregate could be allowed in any high volume surface mix when blended with high friction aggregate (steel or blast furnace slags or sandstone). The findings can be implemented through changes in the specifications and possibly the implementation of a screening test for new materials or mixes based on the laboratory testing and polishing used in this study.

4.1 Approach

Samples of blends of various quantities of polish susceptible aggregates with high friction aggregates were prepared, polished to simulate the action of traffic, and tested in the laboratory for their frictional properties. The variables considered include mix type (HMA and SMA), coarse aggregate type (two polish susceptible aggregates blended with steel furnace slag, blast furnace slag and sandstone), polish susceptible aggregate content, and amount of limestone fine aggregate (in HMA). The experimental design is described in Appendix B, which also summarizes the aggregates and mix designs used in the study. The polishing and testing procedures used to evaluate the changes in friction are reviewed in Appendix C.

Briefly a single nominal maximum aggregate size (NMAS) of 9.5 mm was used. A single binder grade (PG64-22) was used for both types of mix (HMA and SMA) since binder grade is unlikely to affect the frictional properties of the mix after polishing. A high traffic level was used for the initial designs. The rationale for this is that if a polish susceptible aggregate can be shown to be acceptable for high traffic, it will likely be acceptable at lower traffic volumes as well.

This study was coordinated with the Office of Materials Management, which chose and characterized the aggregates evaluated. Materials Management tested the coarse aggregates alone using the British Polishing test for comparison purposes.

To address the objectives of this study required testing coarse aggregates, fine aggregates and some field-produced mixes. These evaluations were conducted separately and are reported separately.

First, target mix designs had to be established. Using example mix designs provided by Materials Management, the research team developed target mix designs for HMA (referred to in the appendices as DGA for dense graded asphalt) and SMA. The design binder content varied to account for the difference in absorption of the various aggregates. The mixes were then produced and compacted to N_{design} in the laboratory to verify the mix design. In general, the gradations of the various mixes varied from the target gradation by less than $\pm 3\%$ and in most cases by less than $\pm 1\%$.

The issue of the effects of the coarse aggregate composition was addressed first. Control mixes with no local coarse aggregate were fabricated with steel furnace slag (SF), air cooled blast furnace slag (ACBF) and sandstone (SStn). These are three high frictional quality aggregates specified by INDOT. These mixes were then replicated with various amounts of one of two polish susceptible (limestone) coarse aggregates, designated PSI and PSII, and natural sand. The amount of polish susceptible coarse aggregate ranged as high as 40%, but not all mixes were made with all the local aggregate amounts. The actual mixes evaluated are detailed in Appendix B.

The mixes were then compacted into slabs approximately 500 mm (20 in) by 500 mm (20 in) square. After cooling, the slabs were tested for their initial friction level and surface texture using a technique developed in earlier research *(3)* and described in Appendix C. This technique uses a Dynamic Friction Tester (DFT) to measure the friction according to ASTM E1911 *(4)* and a Circular Track Meter (CTM) to measure the texture according to ASTM E2157 *(5)*. The polishing action of traffic was simulated using a circular polishing machine, as described in Appendix C. The polisher was stopped periodically to allow CTM and DFT measurements to be made so that changes in the friction and texture of the slabs could be assessed. The friction and texture measurements were used together to calculate the International Friction Index (IFI) according to ASTM E1960 *(6)*. The IFI value is useful because it can be used to compare friction measurements taken with different test equipment. In previous research, a correlation was developed between the IFI measured with the CTM and DFT and the INDOT towed friction trailer friction flag value. The performance of the mixtures with varying amounts of local aggregate can then be compared to the control mixes and to the CTM/DFT friction flag value *(7)*.

After the coarse aggregate evaluation was underway, work began on assessing the effects of increasing amounts of local fine aggregate on the overall frictional resistance of DGA mixes. In this part of the project, mixtures were again prepared with steel slag, air cooled blast furnace slag and sandstone. Then, 10% and 20% of the fine aggregate was replaced by one source of local, polish susceptible (limestone) fine aggregate. The resulting mixes were then fabricated and tested in the same way as in the coarse aggregate study above.

Samples of plant-produced mixes from a test section on SR62 evaluating the field performance of polish resistant aggregate (PRA) were also polished and tested in the lab as a part of this project.

5. RESULTS

The results of the testing done for this research are reported in detail in Appendix D and the results of the characterization testing by the Office of Materials Management are summarized in Appendix E.

In short, the coarse aggregate study showed that adding local, polish susceptible coarse aggregate to a mix with high quality friction aggregates does cause a decrease in friction. As the amount of local aggregate increases, the friction decreases. Some local aggregate, however, can be added and still produce a mixture with adequate frictional properties. The amount of local coarse aggregate that can be added and still provide adequate friction varied between 20% and 30%. Figure 5.1 shows one example; in this case up to 40% local aggregate was blended with steel slag in dense graded HMA. Here, the mixes with 10% and 20% polish susceptible material performed only slightly worse than the control with 100% slag. As the amount of local aggregate increased, however, the friction values began to approach the estimated CTM/DFT friction flag value of about 0.20. In SMA mixes, perhaps higher amounts of local aggregate could be used from a frictional point of view, but there are other considerations, such as particle strength, that may limit aggregate choices.

There appeared to be relatively little difference in the performance of the control and test mixtures from the SR62 test sections, as illustrated in Figure 5.2. The field friction testing results, shown in Appendix E, show similar results. In the field, the PRA only mix had higher friction values in November 2010 and May 2011; in October 2011, the results for all three mixes were similar (within a total range of 2 points) with the PRA only mix being intermediate between the slag only and slag PRA blend. The field friction testing results should be monitored to ascertain how the mixes compare over the long term under actual traffic.

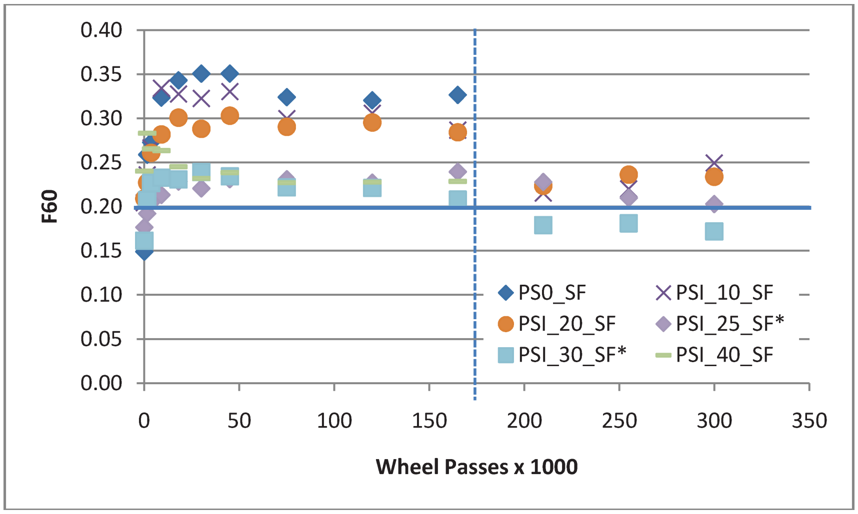

Figure 5.1 International Friction Index(IFI) F60 value for DGA mixes with steel slag and varying amounts of polish susceptible coarse aggregate.

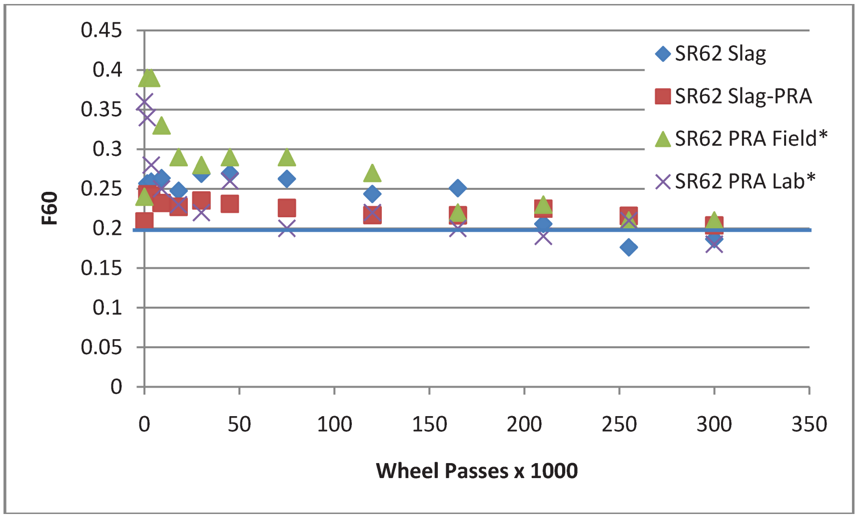

Figure 5.2 IFI F60 value for SR62 study mixtures.

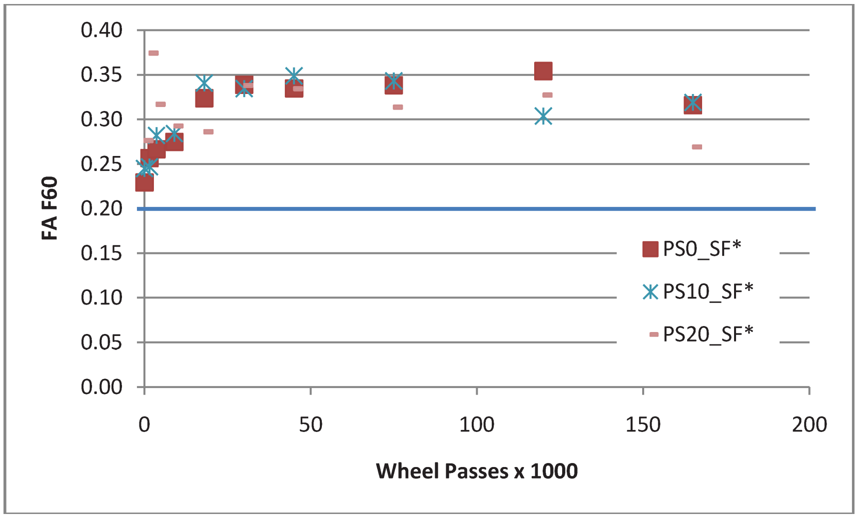

Figure 5.3 F60 results for steel slag and varying polish susceptible fine aggregate contents.

In the evaluation of fine aggregate, there were some testing issues that may reduce the reliability of the results. Specifically, the mixes seem to show excessive changes in the surface texture during polishing. It is not clear if this is related to the specimen fabrication or if these mixes are more sensitive to the shearing action of the tires on the polishing machine. This should be studied in future research. Given that caveat, however, the results generally show that adding a small amount of local fine aggregate may reduce the friction level. If the amount of local fine aggregate is limited and high quality coarse aggregate is used, the friction level may still be adequate, as shown in Figure 5.3 for the DGA mix with steel slag and limestone sand.

6. OVERALL CONCLUSIONS AND OBSERVATIONS

The following conclusions may be drawn about the friction levels of the various mixes based on the preceding results and discussion.

6.1 Coarse Aggregate in DGA

- The control mixes with steel furnace slag, air cooled blast furnace slag and sandstone with no local coarse aggregate provided similar friction levels, with the sandstone being only slightly lower than the two slags.
- Adding a polish susceptible local coarse aggregate to mixes with the three high quality friction aggregates did result in decreases in the friction levels.
- Adding 20% of a local coarse aggregate to the mix with ACBF decreased the friction somewhat but it was still in excess of the friction flag value. The mix with 30% local aggregate was marginal in terms of the flag value.
- With steel slag, adding a polish susceptible aggregate (PSI) lowered the friction level, but there was little difference with 10% and 20% PSI and those mixes provided friction above the friction flag value. The mix with 25% PSI may also be acceptable, but this mix also had the highest macrotexture, which may have increased the friction level. The addition of 30 and 40% PSI coarse aggregate appears to have caused too great a decrease in friction, especially considering that these mixes also had higher macrotexture than the mixes with lower amounts of PSI.
- Adding 20% local coarse aggregate to the mix with sandstone provided friction in excess of the flag value, but the mix with 30% was marginal.
- When added to steel slag coarse aggregate, there was little difference between adding 20% PSI or 20% PSII. The friction of the mix with 20% PSI was slightly lower than the mix with 20% PSII and the control mix was comparable.
- It appears adding 20% local coarse aggregate blended with one of the high quality friction aggregates would still provide adequate friction. This should be validated in the field before considering allowing higher amounts, such as 25%.

6.2 Coarse Aggregate in SMA

- In general, the SMA mixes provided higher friction levels than the DGA and experienced less change in the surface texture.
- The three control mixes provided comparable friction levels.
- Adding 20% PSII to the mix with ACBF lowered the friction level, but it was still greater than the friction flag value.
- Adding increasing amounts of PSII to the mix with steel furnace slag resulted in greater decreases in the friction level. The performance was higher than the flag value up to 40% and there was little difference between 10% and 20% PSII.
- With steel slag, the mixes with 20% PSI and 20% PSII were comparable. Though both provided friction levels below that of the control, they were still well above the flag value.
- Adding 20% PSII to the sandstone mix also lowered the friction but it was still in excess of the flag value.
- Adding 20% local coarse aggregate blended with one of the high quality friction aggregates appears possible from a frictional standpoint, but with SMA mixes in particular, there are other considerations, such as particle strength.

6.3 SR62 Mixes

- Analysis of the results from testing the SR62 mixtures is complicated by the recalibration of the DFT device since the recalibration occurred when some slabs had been polished and tested and others had not. The slag only and slag_PRA mixes had been tested to 165,000 wheel passes before recalibration, but both PRA only mixes were only tested after recalibration.
- Significant variations in the texture depths also complicate the interpretation of the results. The PRA only mixes (both lab fabricated and field sampled) had much higher macrotextures than the other two mixes.
- This is the first time the NCSC has tested field produced mixes that have been stored for any period of time, and it is unknown if this could have affected either the compactability of the mixes or their eventual performance.
- The differences among the mixtures do not appear to be great, but at 165,000 wheel passes, the slag mix is performing the best and the slag_PRA and PRA only mixes are approaching the flag value.
- When additional wheel passes were applied, the slag_PRA and PRA only mixes provided slightly higher friction levels than the slag only mix.
- Based on these results, with the caveats above, the use of the PRA only aggregate does not appear to be problematic from a frictional point of view, at least for low to moderate traffic volumes.
- These results should be compared to field friction test results for further examination.

6.4 Fine Aggregate Study

- The mixes with varying amounts of local fine aggregate exhibited much greater changes in texture depth than the other mixes. In most cases, the texture depth stabilized after about 50,000 wheel passes. It is not known if this is because of poor compaction of the mixes or their greater sensitivity to the shearing action of the tires on the polishing machine. The change in the texture may have been causing new, unpolished aggregate surfaces to be exposed, which would affect the friction results. Since the texture generally did not change much after 50,000 passes, examining the terminal friction levels seems reasonable.

- The control mix with ACBF provided a lower friction level than the control with steel slag or sandstone.
- The results of testing mixes with ACBF and different amounts of local fine aggregate were erratic but the friction levels at 165,000 wheel passes appear to be acceptable.
- When local fine aggregate was blended with steel slag, there was little difference between the control and 10% local aggregate. The mix with 20% local fine aggregate also appeared to provide acceptable friction levels. This supports the current INDOT standard specifications, which allow up to 20% of the total aggregate in HMA surface mixes to be crushed limestone.
- The friction levels were above the flag value for the mixes with 0%, 10% and 20% local fine aggregate when blended with sandstone and the results were comparable at 165,000 wheel passes. The sandstone only control, however, provided higher friction levels than the mixes with local fine aggregate between 50,000 and 120,000 passes; it is unknown if the last data point for the control mix is accurate or an outlier.
- The overall results of the fine aggregate study are less conclusive than those of the coarse aggregate study. Nonetheless, it does appear that a small amount of local fine aggregate can be added to DGA mixtures without detrimental effect on the resulting friction levels. This seems reasonable since it is widely held that most of the frictional resistance of asphalt mixtures is provided by the coarse aggregate. Before the specifications are greatly changed, it would be prudent to do additional research in the lab or field or preferably both.

6.5 General Observations

- This study evaluated only one size of mix, 9.5 mm. Previous research *(8)* has shown that larger nominal aggregate size mixes may provide higher friction levels. There is also evidence that smaller nominal aggregate size mixes may require higher frictional quality aggregates, in part at least, because of their reduced macrotexture. Extension of these findings and recommendations to other mix sizes should be done cautiously and preferably should be guided by additional research in the lab and/or field.
- Another previous study evaluated the potential effects of poor quality aggregate in reclaimed asphalt pavement (RAP) if the RAP is reused in high volume surface mixes. The final report on that project *(9)* suggests that up to 20%–25% poor frictional quality RAP could be used in surface mixes without detrimental effect on the friction level. The possible allowable local aggregate levels recommended in this study are in substantial agreement with that other study. This is reasonable since, once in the mix, the aggregate behaves the same whether it came from RAP or was virgin aggregate, at least in terms of friction.
- The laboratory techniques used in this study are definitely useful since trial mixes or new materials can be evaluated without risk to the public. Additional refinement is recommended, however, to develop them more fully and address some of the problem noted in this study. Particularly, there is a need to examine the compaction process, equipment calibration and data interpretation. Further comparisons of the lab and field measured friction levels to further refine the friction flag value would also be extremely useful. The procedures could then be used as a screening test to approve new aggregates or mix types for field trials, similar to the approach in the current ITM 214 *(1)*.
- These results may be useful for opening up the specifications somewhat but a conservative approach is recommended until field testing verifies the accuracy of the lab results.

7. RECOMMENDATIONS FOR IMPLEMENTATION

The results of this study demonstrate that local, polish susceptible aggregates can be used to replace a portion of high quality friction aggregates in HMA and SMA surface mixtures without detrimental effect on friction. Replacing some of the premium materials with locally available aggregates will help to reduce costs while maintaining safety. In addition to reduced material costs (by using less of the "premium" high quality aggregates), hauling costs and energy consumption will also be reduced by using more materials from the local area.

Based on the results of this study, an allowable threshold of 20% local coarse aggregate and 20% local fine aggregate could be allowed for high volume surface mixes when blended with high quality friction aggregates, namely steel furnace slag, air cooled blast furnace slag or sandstone. This finding could be implemented by revising section 904.03 of the standard specifications.

In addition, the laboratory evaluation procedures used in this study could be implemented as a screening test for new materials or new types of mixtures. An ITM could be written similar to ITM 214 *(1)* to evaluation whether new materials should be placed in field trial sections. Such a screening test would allow contractors, material suppliers and INDOT to ascertain whether a material warrants further investigation before the effort and funds are invested in construction of a field trial.

REFERENCES

1. ITM 214. *Acceptance Procedures for Polish Resistant Aggregates*. Indiana Department of Transportation, Indianapolis.
2. Bruner, D. W., J. C. Choi, and T. R. West. *Development of a Procedure to Identify Aggregates for Bituminous Surfaces in Indiana*. Publication FHWA/IN/JHRP-95/11. Joint Highway Research Project, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 1995. doi: 10.5703/1288284313187.
3. Kowalski, K. R., S. McDaniel, and J. Olek. Development of a Laboratory Procedure to Evaluate the Influence of Aggregate Type and Mixture Proportions on the Frictional Characteristics of Flexible Pavements. *Journal of the Association of Asphalt Paving Technologists*, Vol. 77, 2008, pp. 35–70.

4. ASTM Standard E1911. *Standard Test Method for Measuring Paved Surface Frictional Properties Using the Dynamic Friction Tester*. ASTM International, West Conshohocken, Pennsylvania.
5. ASTM Standard E2157. *Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter*. ASTM International, West Conshohocken, Pennsylvania.
6. ASTM Standard E1960. *Standard Practice for Calculating International Friction Index of a Pavement Surface*. ASTM International, West Conshohocken, Pennsylvania.
7. Kowalski, K. J., R. S. McDaniel, J. Olek, A. Shah, and S. Li. Development of the International Friction Index Flag Value. Paper No. 705, presented at the Tenth International Conference on Application of Advanced Technologies in Transportation, Athens, Greece, May 27–31, 2008.
8. Kowalski, K. J., R. S. McDaniel, and J. Olek. *Identification of Laboratory Technique to Optimize Superpave HMA Surface Friction Characteristics*. Publication FHWA/IN/JTRP-2010/06, Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2010. doi: 10.5703/1288284314265.
9. McDaniel, R. S., K. J. Kowalski, and A. Shah. *Evaluation of Reclaimed Asphalt Pavement for Surface Mixtures*. Publication FHWA/IN/JTRP-2012/03. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2012. doi: 10.5703/1288284314665.

APPENDIX A
LITERATURE REVIEW

INTRODUCTION

It is well known that pavement friction depends on both the microtexture of the aggregates themselves and the macrotexture of the overall pavement surface. The microtexture is determined by the types of aggregates used, and the macrotexture depends on the sizes of the aggregates and the overall composition of the pavement surface. Both of these factors can be affected by blending different types and amounts of aggregates. This literature review summarizes the factors affecting pavement frictional resistance and how pavement friction is characterized.

SKID RESISTANCE OF PAVEMENTS

The frictional properties of surface mixtures are significantly related to highway safety. According to National Transportation Safety Board and FHWA reports *(1)*, approximately 13.5% of fatal accidents and 25% of all accidents occur on wet pavements.

PHYSICS OF FRICTION

The classic theory of friction force is as known "Coulomb Friction," expressed as follows *(2)*:

$$F_f = \mu \times N$$

where: F_f = the maximum possible force exerted by friction;
μ = the coefficient of friction;
N = the normal force to the contact surface.

The friction force between a tire and pavement develops through adhesion and hysteresis at the contact surface where the tire rubber and pavement surface interact *(3,4)*. This can be expressed as:

$$F_\mu = F_a + F_h$$

where: F_μ = friction force;
F_a = adhesion force developed by the interface shear strength and contact area;
F_h = hysteresis force generated from losses of rubber materials damping.

A detailed description of the mechanisms of adhesion and hysteresis force shows that the first component, the adhesion force, is produced by the rubber molecules that are in direct contact with the contact surface *(5)*. When there is a speed difference between the rubber and contact surface, the rubber will be stretched. As the tire moves across the surface, some molecular bonds between the tire and surface will be broken and new ones will form. Breaking and forming bonds takes energy and produces an adhesion force.

Hysteresis, the second component, is caused by deformation of the rubber as the tire moves over the surface. The rubber is compressed in some areas and stretched in others. Friction caused by these deformations makes the tire heat up. Again, all this takes energy, and thus gives a force known as hysteresis *(5)*.

The relative proportions of adhesion and hysteresis vary depending on the properties of the tire, surface, weight on the tire and other factors. If the pavement is wet and rough, the hysteresis component will be dominant over adhesion. The water film on the pavement acts as a lubricant, decreasing the adhesion force. In addition, the roughness of the surface causes the tire to deform significantly, which increases the hysteresis force. In contrast, if the pavement is dry and smooth, adhesion will be the dominant force because the rubber can bond to the pavement surface; hysteresis is reduced because the tires do not deform as much on a smooth surface *(5)*.

FACTORS AFFECTING FRICTION

There are a number of factors that influence the frictional properties of HMA pavements. The most important factor is whether the surface conditions are wet or dry. Pavements under dry conditions are more capable of providing appropriate skid resistance. Hence, research is mostly focused on the frictional resistance under wet conditions when pavements can be extremely slippery. The factors affecting friction are discussed below:

Traffic wear. Shankar *(6)* applied statistical and economic methods to analyze accident frequencies and concluded that higher Annual Average Daily Traffic (AADT) may cause reduced frictional resistance and increase the possibility of fatal accidents. Shupe *(7)* also pointed out that an accumulation of oil, worn rubber and dust particles on the pavement has a significant effect on the friction characteristics.

Water film. When water is present on the road surface, it can reduce the adhesion force of tires by interfering with the formation of bonds between the rubber and pavement. Shupe *(7)* indicated that tires can have good interaction with the pavement through a 0.001 in water film but the friction force will greatly diminish if the water film is deeper. Kulakowski *(8)* conducted research both in the laboratory and in situ to investigate the effect of water film thickness on tire and pavement friction. The results showed that at 64 km/h (40 mph) as little 0.05 mm (0.002 in) of water could reduce dry surface friction by 20% to 30%.

Tire effect. Kennedy *(9)* reported that the adhesion force of rubber tires may increase and the hysteresis force may decrease when the temperature increases. However, the combined effects of both components will lead to lower skid resistance measurements as temperature increases. Shupe *(7)* also indicated that proper tire pressure is necessary to penetrate the water film and maintain adequate friction.

Macro- and microtexture. Today, it is generally agreed that pavement friction depends on both macro and microtexture. An international standard for road surface texture terminology has been established by the Technical Committee on Surface Characteristics of the World Road Association's Permanent International Association of Road Congress (PIARC) *(10)*.

Megatexture: Wavelength = 50 mm to 500 mm (2 to 20 in)
Macrotexture: Wavelength = 0.5 mm to 50 mm (0.02 to 2 in)
Microtexture: Wavelength = 1 µm to 0.5 mm (0.0004 to 0.02 in)

Thus, microtexture is defined as small-scale texture up to about 0.5 mm (0.02 in) of the aggregate particles, and macrotexture is larger texture between about 0.5 and 15 mm (0.02–0.59 in) created by the valleys between aggregate particles on the surface *(10,11)*. Thus, the macrotexture of the pavement surface is largely a result of the type and size of the HMA mixture (gradation), while the microtexture is affected by the mineralogy of the aggregates. For wet pavement friction, macrotexture helps to provide drainage channels for the bulk of the water to escape, and microtexture breaks the last thin film of water coating the aggregate particles to allow aggregate-tire contact *(9,11,13)*. Microtexture has an effect on friction at all speeds, but macrotexture assumes a greater role at speeds of 64 kph (40 mph) or higher *(12)*. Kennedy *(9)* said that microtexture predominates at speeds up to only 50 kph (31 mph). Macrotexture is the controlling factor in the speed dependency of friction. In other words, the microtexture controls the friction level at low speeds, and the macrotexture controls how the friction changes with increasing speed *(9)*.

Yager and Bühlmann *(14)* investigated the role of pavement macrotexture in draining airport runways. They noted that macrotexture is very important, but added that macrotexture alone cannot define the frictional properties of a pavement. It is important to assess both the macrotexture and the microtexture.

Kandhal and Parker noted that, because of the complexities and many interrelated factors involved in frictional resistance of an asphalt pavement, "a test that measures only the microtexture of the coarse aggregate may not be an efficient means of evaluating suitability for polish and friction resistance" *(15)*.

Forster *(16)* reported a correlation between skid resistance, as indicated by British Portable Tester numbers *(BPN)* measured by British Pendulum Tester (*microtexture*), and the texture properties measured by the Sand Patch test (*macrotexture*). An image analysis system was adopted to understand and determine optimal macro and microtexture parameters. He concluded that the overall texture had a significant influence on skid resistance measurements.

Mixture type. The type of mixture can affect the overall aggregate gradation, which in turn affects the macrotexture. For example, in previous research *(17)* conducted by the North Central Superpave Center (NCSC), friction properties of conventional dense-graded HMA, SMA and Porous Friction Course (PFC) were investigated and evaluated in the field. The PFC was composed of 90% steel slag with 10% sand; the SMA consisted of 80% steel slag, 10% stone sand (from a different source than the PFC sand) and 10% mineral filler; the HMA was made of the same source of steel slag blended 50/50 percent with coarse dolomite. This research revealed that the PFC provided the highest friction value, followed by the SMA. Both the PFC and SMA had substantially higher friction values than the conventional HMA even though they were tested before opening the road to traffic. The friction values for the PFC and SMA would be expected to increase after traffic wears away the binder film coating on aggregate particles.

Seasonal variance. Several reports *(7,8,9,18)* indicated that during dry periods, frictional resistance is dominated by microtexture. But when the road is wet, the pavement macrotexture has a greater effect because it can provide channels to carry the water away from the tire-pavement interface. For example, Kennedy *(9)* indicated that road surfaces in England are wet only 15% of the time in summer months (May to September). Under these dry conditions, polishing predominates and causes low skid resistance values. On the other hand, though the roads are wet 60% of the time in winter, the frictional measurements tend to be as much as 25% higher. Shupe *(7)* gave an explanation of this phenomenon. During the dry period, tires on the highway polish individual exposed pieces of aggregate and produce fine dust. Those dust particles can act as additional lubrication, a so-called "ball-bearing" effect, and may result in a slippery pavement condition. During the wet period, rainfall may wash the dust from the pavement. Therefore, the pavement becomes relatively coarser and increases the skid resistance.

Aggregate properties. Dames *(19)* observed that frictional resistance depends not only on the mineralogical properties of the aggregate but also on the grain size and distribution, or the surface texture. He also noted that the influence of the sand fraction in the overall gradation may be more significant than previously thought.

Colony, in a laboratory study of bituminous surfaces, noted that the importance of the fine aggregate fractions was under-appreciated, especially at low speeds *(20)*. Williams found that the fine aggregate angularity, percent passing the 0.600 μm sieve, aggregate bulk specific gravity and particle shape were the aggregate properties which had the greatest influence on pavement friction *(21)*.

Carbonate rocks are the major source of mineral aggregates in the Midwest. Goodwin *(22)* and Aughenbaugh and Lounsbury *(23)* reported there is a belt of Silurian rocks from metropolitan Chicago area to northwestern and east-central Indiana, where limestone ($CaCO_3$) and dolomitic limestone ($Ca\ (Mg)CO_3$) are quarried.

Shupe *(7)* concluded that some limestone aggregates consisting of pure calcium carbonate should not be used for high volume roads because of their tendency to polish. Other types of carbonate aggregates composed of dolomitic limestone would be expected to provide adequate skid resistance. He also indicated that the best method of predicting the polishing characteristics of an aggregate in a specific mixture is to duplicate the mixture in the laboratory, subject it to an accelerated polishing procedure, and evaluate the change in frictional resistance.

Aughenbaugh and Lounsbury *(23)* investigated the carbonate aggregates in northern part of Indiana. They sampled aggregates from 28 sites and analyzed them by petrographic analysis methods. They reported that aggregates from eastern Indiana had higher Los Angeles abrasion losses and absorption. Another finding was that the variation in the calcium-magnesium ratio had no apparent effect on abrasion losses or absorption test, except as they affected the texture.

West et al. *(18,24)* investigated the friction resistance of aggregates in Indiana. Aggregate coupons were made for the British wheel test (ASTM D3319 *(25)*) and British pendulum test (ASTM E303 *(26)*). Results indicated that dolomites blended with slag could provide high friction resistance for high traffic volume roads. Crushed gravel and some specific limestones were also proven acceptable for friction if the aggregate properties could meet standard requirements. Furthermore, for gravels, the frictional resistance correlated well with the freezing and thawing soundness test (AASHTO T103 *(27)*), absorption test (ASTM C127 *(28)*), and percentage of crushed gravel and metamorphic rocks; for carbonate aggregates, the acid insoluble residue (ASTM D3042 *(29)*) is the most influential factor for limestone; while the absorption test and elemental magnesium (M_g) content test (ASTM C602 *(30)*) are the most important evaluation methods for dolomite. However, although a minimum 10.3% elemental Mg content is advised, dolomite with less than 10.3% could be also regarded as a potential aggregate for surface courses if the properties of absorption and soundness loss (ASTM C88 *(31)*) pass other specifications.

As reported in *NCHRP Synthesis 291*, Henry *(32)* conducted a worldwide survey regarding pavement friction. One of the survey responses about evaluation methods for aggregate polishing revealed that the Los Angeles (LA) Abrasion test *(*AASHTO T96 *(33)*) is the most commonly used method. The British Wheel test is second, most commonly in Europe. Additionally, Quebec and Slovakia included the Mean Texture Depth *(*MTD, measured by sand patch test) with the British pendulum test for mixture evaluations. In Japan, instead of MTD, the Dynamic Friction Tester (DFT) is used in addition to the British pendulum test to evaluate the frictional properties of laboratory mixtures.

Rogers et al. *(34)* concluded that the friction performance is determined by a proper mix design and the use of satisfactory aggregates. They reached similar conclusions as Shupe *(7)* that calcium carbonate rocks are generally softer (Mohs hardness between 3 and 3.5) and give significantly lower values in an aggregate friction resistance test than other types of aggregates. Rogers et al. also suggested and compared several testing methods to estimate wear-resistance (indicating macrotexture) and polish resistance (indicating microtexture). They suggested the Aggregate Abrasion Value test (AAV) *(*BS 812), LA abrasion test, and Micro-Deval abrasion (AASHTO T327 *(35)*) are good indicators of aggregate wearing resistance; while the Polished Stone Value test (PSV) (BS 812) is a suitable tool to evaluate polish resistance. They also found that good AAV value coincides with a low LA abrasion weight loss. However, an aggregate with high LA abrasion loss might still retain good resistance to abrasion. It was implied that LA abrasion is not a reliable test. Results from Micro-Deval tests generally agree with the AAV. However, AAV is more time consuming and expensive compared to the Micro-Deval test. Cooley *(36)* and Prowell *(37)* also reached similar conclusions that results from the LA abrasion and Micro-Deval tests might give opposite answers about the frictional resistance of aggregates.

Doty *(38)* reported on a comparison between friction and surface texture, as measured by the sand patch test and outflow meter. There was a general trend of higher friction with increasing texture depth for a variety of surface types including open and dense graded asphalt, sealed surfaces, and polished and grooved PCC. Surface texture alone, however, did not yield a strong enough relationship to establish a minimum texture depth criterion for use as a specification limit.

Blending of aggregates. Blending of high and low friction aggregates is an attractive possibility since this may allow the use of lower frictional quality, locally available aggregates, which may result in lower costs. Many states allow blending of high and low frictional resistance aggregates routinely; for example, Virginia has allowed this type of blending since about 1955 *(39)*.

Liang *(40)* conducted research on blending high and low skid resistance aggregates. He found that a 50/50 blend of the high and low skid resistance aggregates he tested met the frictional requirements, but he suggested that a 60/40 blend of high and low resistance aggregates might be more acceptable in general.

A 1980 study in Louisiana *(41)* discussed the possibility of differential wear when blending aggregates. Differential wear may occur when a softer aggregate polishes more quickly than a harder, higher friction aggregate with which it has been blended. The more resistant aggregate may then protrude or "perch" on the surface and be more exposed to traffic. The study concluded that differential wear can be advantageous if the resistant aggregate is angular with sharp edges. If, however, the resistant aggregate does not have sharp edges, differential wear may result in poorer performance. The study also concluded that blending aggregates could work with some of the materials available in the state, but not all.

In Israel, only basalt aggregates were allowed for use on high volume roadways in order to provide high friction. Basalt, however, is not plentiful, so extensive usage resulted in high prices. A research project there evaluated the possibility of blending basalt and dolomite to reduce costs while maintaining adequate friction. The study evaluated various blends in the laboratory using the British polishing test to determine the Polish Stone Value (PSV). The lab study was followed with a field trial of eight different combinations of basalt and dolomite in 19 and 25 mm HMA and SMA surfaces. The results showed that basalt only mixes were superior to dolomite only mixes and the blended basalt-dolomite mixes were nearly as good as the basalt only. Based on this study, the Israeli specifications were changed to allow decreasing the basalt content to a minimum of 40% (by weight) of the total aggregate and 60% (by weight) of the material retained on the 4.75 mm sieve *(42)*.

METHODS FOR MEASURING FRICTION

Locked wheel device. Wet pavement friction measurements can be obtained by using the ASTM E274 *(43)* towed friction trailer. The ASTM towed friction trailer allows two types of tires for friction evaluations including the Standard Rib Tire for Pavement Skid-Resistance Test (ASTM E501 *(44)*) and Standard Smooth Tire for Pavement Skid-Resistance (ASTM E524 *(45)*). The Indiana Department of Transportation (INDOT) routinely uses the blank or smooth test tire on the trailer, shown as Figure A.1. A locked tire with 24 psi (165 kPa) of pressure sliding on a wetted surface, under a constant speed and load, is used to measure the steady-state friction force. When the towed trailer reaches the standard test speed of 40 mph (64 km/h), the brake is locked after the watering system provides a water film of 0.02 in (0.5 mm.) The friction data is reported as the Skid Number or Friction Number (SN40).

Several studies have shown that the friction measured with the smooth tire is related to both the macrotexture and microtexture of the pavement *(46,47)*. However, Henry *(32)* reported that most states preferred the rib tire instead of the smooth tire. The possible reasons could be that the frictional value measured with the smooth tire is much lower than the ribbed tire and there are difficulties comparing with historical data if the tire is changed from previous practice. Nonetheless, Indiana made the change from the rib to smooth tire in the 1990s.

Figure A.1 ASTM E274 *(43)* towed trailer of INDOT.

Measurement of macrotexture. The traditional method for macrotexture measurement is the Sand Patch test (ASTM E965 *(48)*). The method consists of spreading a fixed volume of dry Ottawa sand or glass spheres over the surface and working them into the surface texture in a circular pattern. The sand is spread until it is flush with the tops of any surface asperities. The area covered by the sand and the known volume of sand allow calculation of the average texture depth, called the Mean Texture Depth (MTD). The method and equipment are simple, but significant variability (poor repeatability) in the measurements has been reported. In addition, only an average texture depth can be obtained. No further analysis of the nature of that texture depth can be accomplished.

The Circular Texture Meter (CTM; also referred to as Circular Track Meter), shown in Figure A.2, is an advanced way to measure pavement macrotexture. The Mean Profile Depth *(*MPD) of a pavement surface can be measured with the CTM. Prowell et al. *(49)* observed that the CTM produced comparable macrotexture results to the sand patch method on the National Center for Asphalt Technology *(*NCAT) Test Track. However, the CTM is easier for the technician to operate and has less operator error than the sand patch method. The CTM, described as ASTM E2157 *(50)*, uses a Charge Coupled Device (CCD) laser displacement sensor to measure the surface profile. The laser sensor is mounted on an arm that rotates around a central point at a fixed distance above the pavement and measures the change in elevation of points on the surface. The laser spot size is 70 mm and the vertical resolution is 3 mm. Each test takes about 40–45 seconds *(51,52)*. The CTM profile can be analyzed to determine more about the nature of the texture. One advantage of this method is that eight separate arcs of the circle can be analyzed.

Measurement of microtexture. Microtexture, on the other hand, can be measured in the field or the laboratory using a device such as the British Pendulum Tester or the Dynamic Friction Tester (DFT). The British pendulum has been used for many years; however, it yields more variable results and requires more skilled personnel than the DFT.

As shown in Figure A.3, the DFT is a portable device that allows direct measurement of the surface friction of a variety of surfaces, including pavements. Described in ASTM E1911 *(53)*, the DFT consists of a horizontal spinning disk fitted with three spring-loaded rubber sliders that contact the paved surface. The standard sliders are made of the same type of rubber used in friction test tires, though other materials are available for other

Figure A.2 Circular Texture Meter.

Figure A.3 Dynamic friction tester in use.

applications. The disk rotates at tangential velocities up to 80 kph (55 mph). Water flows over the surface being tested, so wet friction is measured as done with the towed friction trailer. The rotating disk is then dropped onto the wet surface and the friction is continuously measured as the disk slows. This continuous measurement allows determination of the speed dependency of the surface friction *(51,52)*. The DFT is relatively small, approximately 511 mm (20.1 in) square and weighing about 11 kg. The tested area is a circular path with a diameter of about 284 mm (11.2 in). A small tank is used to provide water and a personal computer is used for control of the test and data acquisition.

CALCULATION OF INTERNATIONAL FRICTION INDEX (IFI)

Henry et al. *(54)* found that International Friction Index (IFI) can be determined by combining the measurements from the DFT and CTM. IFI was developed in Europe to harmonize friction measurements made in various countries and measured by any number of different devices. The IFI allows these various measurements to be reported in common measurement terms.

There are three steps to determine the *IFI*:

1. The speed constant (S_p) is a function of the pavement macrotexture and can be defined by following equation:

   $$S_p = a + b \cdot TX$$

   where TX is the pavement macrotexture and a and b are constants depending on how the macrotexture is measured.

2. The friction number *FR60* is the adjusted value at a slip speed of 60 km/h converted by *FRS*, the friction measurement reported by friction measurement device at slip speed *S*:

   $$FR60 = FRS \cdot e^{\frac{S-60}{Sp}}$$

3. Friction number (F_{60}) is defined as

   $$F_{60} = A + B \cdot FRS \cdot e^{\frac{S-60}{Sp}}$$

   where, A and B are constants based on specific friction measurement device.

For the CTM and DFT, MPD (macrotexture) is used to determine the S_p as:

$$S_p = 14.2 + 89.7 \cdot MPD$$

When using the DFT to measure friction, the DFT20 value, which means the friction measurement (microtexture) conducted by DFT at slip speed of 20 km/h, is recommended for predicting the F_{60}. Therefore, the friction number (F_{60}) can be obtained by:

$$F_{60} = 0.081 + 0.732 \times DFT_{20} \times \exp(-40/S_p)$$

As described in a previous JTRP report *(55)*, the CTM and DFT can both be used in the laboratory and in the field. This research, and other projects *(56)*, refined a method for testing asphalt mixtures in the laboratory *(57)* to estimate their anticipated frictional performance in the field, allowing the evaluation of differing aggregate blends. Correlations have also been developed in Indiana between the ASTM towed friction trailer and the IFI determined using the DFT and CTM *(58)*. These techniques are further described in Appendix C.

REFERENCES

1. Kuemmel, D. A., R. C. Sontag, J. A. Crovetti, Y. Becker, J. R. Jaeckel, and A. Satanovsky. *Investigative Study of the Italgrip System, Noise Analysis*. Publication WI/SPR-02-00, Wisconsin Department of Transportation, Madison, Wisconsin, 2000.
2. Tipler, P. *Physics for Scientists and Engineers, Vol. 1: Mechanics, Oscillations and Waves, Thermodynamics*. 4th ed., W. H. Freeman, New York, 1998.
3. Kummer, H. W. United Theory of Rubber and Tire Friction. *Engineering Research Buletin B-94*. The Pennsylvania State University, State College, Pennsylvania, 1966.
4. French, T. *Tire Technology*. Adam Hilger, Bristol, United Kingdom, 1989.
5. Heremans, B. Chapter 1: Tires. In *R/C Car Handling*. 2001. http://home.scarlet.be/∼be067749/58/, accessed on January 4, 2012.
6. Shankar, V. N., F. L. Mannering, and W. Barfield. Effect of Roadway Geometrics and Environmental Factors on Rural Freeway Accident Frequencies. *Accident Analysis and Prevention*. Vol. 27, No. 3, 1995, pp. 371–389. doi: 10.1016/0001-4575(94)00078-Z.
7. Shupe, J. W. Section 20: Pavement Slipperiness. In *Highway Engineering Handbook*, Woods, K. B., D. S. Berry, and W. H. Goetz, Eds. McGraw-Hill Book Co. Ltd., Columbus, Ohio, 1960, pp. 1–27.
8. Kulakowski, B. T., and D. W. Harwood. Effect of Water-Film Thickness on Tire-Pavement Friction. In *ASTM STP 1031: Surface Characteristics of Roadways: International Research and Technologies*, Meyer, W. E., and J. Reichert, Eds. American Society for Testing and Materials, Philadelphia, 1990, pp. 50–60.
9. Kennedy, C. K., A. E. Young, and I. C. Butler. Measurement of Skidding Resistance and Surface Texture and the Use of Results in the United Kingdom. In *ASTM STP 1031: Surface Characteristics of Roadways: International Research and Technologies*, Meyer, W. E., and J. Reichert, Eds. American Society for Testing and Materials, Philadelphia, 1990, pp. 87–102.
10. World Road Association (PIARC). *Report of the Committee on Surface Characteristics*. XVIII World Road Congress, Brussels, Belgium, 1987.
11. Deway, G. R., A. C. Robords, B. T. Armour, and S. R. Looman. Aggregate Wear and Pavement Friction. In *TRB*

Annual Meeting CD-ROM. Transportation Research Board, Washington, D.C., 2001.

12. Hill, B. J., and J. J. Henry. Surface Materials and Properties Related to Seasonal Variations in Skid Resistance. In *ASTM STP 763: Pavement Surface Characteristics and Materials*, C. M. Hayden, Ed., American Society for Testing and Materials, Philadelphia, 1982, pp. 45–60.
13. Rose, J. G., B. M. Gallaway, and K. D. Hankins. Macrotexture Measurements and Related Skid Resistance at Speeds from 20 to 60 Miles per Hour. *Highway Research Record 341*, Highway Research Board, Washington, D.C., 1970, pp. 33–45.
14. Yager, T. J., and F. Bühlmann. Macrotexture and Drainage Measurements on a Variety of Concrete and Asphalt Surfaces. In *ASTM STP 763: Pavement Surface Characteristics and Materials*, Hayden, C. M., Ed. American Society for Testing and Materials, Philadelphia, 1982, 16–30.
15. Kandhal, P. S., and F. Parker, Jr. *Aggregate Tests Related to Asphalt Concrete Performance in Pavements*. NCHRP Report 405. Transportation Research Board of the National Research Council. National Academy Press, Washington, D.C., 1998.
16. Forster, S. W. Pavement Microtexture and Its Relation to Skid Resistance. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1215, Transportation Research Board of the National Academies, Washington, D.C., 1989, pp. 151–164.
17. McDaniel, R. S., W. D. Thornton, and J. G. Dominguez. *Field Evaluation of Porous Asphalt Pavement*. Publication SQDH 2004-3. North Central Superpave Center, Purdue University, West Lafayette, Indiana, 2004.
18. West, T. R., J. C. Choi, D. W. Bruner, H. J. Park, and K. H. Cho. Evaluation of Dolomite and Related Aggregates Used in Bituminous Overlays for Indiana Pavements. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1757. Transportation Research Board of the National Academies, Washington, D.C., 2001, pp. 137–147.
19. Dames, J. The Influence of Polishing Resistance of Sand on Skid Resistance of Asphalt Concrete In *ASTM STP 1031: Surface Characteristics of Roadways-International Research and Technology*, W. E. Meyer and J. Reichert, Eds., American Society for Testing and Materials, Philadelphia, 1990, pp. 14–29.
20. Colony, D. C. *Influence of Mix Design Variables on Initial Surface Friction of Bituminous Concrete*. Publication FHWA/OH-88-001. Federal Highway Administration and Ohio Department of Transportation, Columbus, Ohio, 1987.
21. Williams, S. G. *Surface Friction Measurements of Fine-Graded Asphalt Mixtures*. University of Arkansas, Fayetteville, Arkansas, 2008.
22. Goodwin, J. H. Geology of Carbonate Aggregate Resources of Illinois. *Illinois Mineral Notes 87*, Illinois State Geological Survey, Champaign, Illinois, 1983.
23. Aughenbaugh, N. B., and R. W. Lounsbury. Petrographic Analysis of Northern Indiana Carbonate Aggregates. *The Ohio Journal of Science*, Vol. 66, No. 2, 1966, pp. 179–187.
24. West, T. R., and K. H. Cho. *Development of a Procedure to Identify Aggregate for Bituminous Surfaces in Indiana*. Publication FHWA/IN/JTRP-2000/28, Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2001. doi: 10.5703/1288284313186.
25. ASTM Standard D3319. *Standard Practice for Accelerated Polishing of Aggregates Using the British Wheel*. ASTM International, West Conshohocken, Pennsylvania.
26. ASTM Standard E303. *Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester*. ASTM International, West Conshohocken, Pennsylvania.
27. AASHTO T103. *Standard Method of Test for Soundness of Aggregates by Freezing and Thawing*. American Association of State Highway and Transportation Officials.
28. ASTM Standard C127. *Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate*. ASTM International, West Conshohocken, Pennsylvania.
29. ASTM Standard D3042. *Standard Test Method for Insoluble Residue in Carbonate Aggregates*. ASTM International, West Conshohocken, Pennsylvania.
30. ASTM Standard C602. *Standard Specification for Agricultural Liming Materials*. ASTM International, West Conshohocken, Pennsylvania.
31. ASTM Standard C88. *Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate*. ASTM International, West Conshohocken, Pennsylvania.
32. Henry, J. J. *Evaluation of Pavement Friction Characteristics, A Synthesis of Highway Practice*. NCHRP Synthesis No. 291. National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 2000.
33. AASHTO T96. *Standard Method of Test for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*. American Association of State Highway and Transportation Officials.
34. Rogers, C., B. Gorman, and B. Lane. Skid-Resistance Aggregates in Ontario. Presented at 10th Symposium, International Center for Aggregates Research, Baltimore, 2002.
35. AASHTO T327. *Standard Method of Test for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus*. American Association of State Highway and Transportation Officials.
36. Cooley, L. A. Jr., M. S. Huner, and R. S. James. *Micro-Deval Testing of Aggregates in the Southeast*. NCAT Report 02-09. National Center for Asphalt Technology, Auburn University, Auburn, Alabama, 2002.
37. Prowell, B. D., J. Zhang, and E. R. Brown. *Aggregate Properties and the Performance of Superpave-Designed Hot Mix Asphalt*. NCHRP Report 539, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 2005.
38. Doty, R. N. Study of the Sand Patch and Outflow Meter Methods of Pavement Surface Texture Measurements. In *ASTM STP 583: Surface Texture Versus Skidding: Measurements, Frictional Aspects, and Safety Features of Tire-Pavement Interaction*. American Society for Testing and Materials, Philadelphia, 1975, pp. 42–60.
39. Sherwood, W. C., and D. C. Mahone. *Predetermining the Polish Resistance of Limestone Aggregates*. Highway Research Record 341. Highway Research Board, Washington, D.C., 1970, pp. 1–10.
40. Liang, R. *Blending Proportions of High Skid and Low Skid Aggregate*. Publication FHWA/OH-2003/014. Federal Highway Administration and Ohio Department of Transportation, Columbus, Ohio, 2003.
41. Ashby, J. T. Jr. *Blended Aggregate Study, Final Report*. Research Report No. FHWA/LA-80/145. Louisiana

Department of Transportation and Development, March 1980.

42. Ravina, A., and S. Nesichi. Development of Skid Resistant Hot Asphalt Mixtures by Blending Aggregates from Different Sources. Presented at 3rd International Surface Friction Conference, Safer Road Surfaces—Saving Lives, Queensland, Australia, May 2011, http://www.saferroads.org.uk/2011papers.asp, accessed January 4, 2012.
43. ASTM Standard E274. *Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire*. ASTM International, West Conshohocken, Pennsylvania.
44. ASTM Standard E501. *Standard Specification for Standard Rib Tire for Pavement Skid-Resistance Tests*. ASTM International, West Conshohocken, Pennsylvania.
45. ASTM Standard E524. *Standard Specification for Standard Smooth Tire for Pavement Skid-Resistance Tests*. ASTM International, West Conshohocken, Pennsylvania.
46. Henry, J. J., and K. Saito. Skid Resistance Measurements with Blank and Ribbed Test Tires and Their Relationship to Pavement Texture. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 946. Transportation Research Board of the National Academies, Washington, D.C., 1983, pp. 38–43.
47. Li, S., S. Noureldin, and K. Zhu. *Upgrading the INDOT Pavement Friction Testing Program*. Publication FHWA/IN/JTRP-2003/23, Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2004.
48. ASTM Standard E965. *Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique*. ASTM International, West Conshohocken, Pennsylvania.
49. Prowell, B. D., and D. I. Hanson. Evaluation of Circular Texture Meter for Measuring Surface Texture of Pavements. In *Transportation Research Board Annual Meeting CD-ROM 05-1981*. Transportation Research Board, Washington, D.C., 2005.
50. ASTM Standard E2157. *Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter*. ASTM International, West Conshohocken, Pennsylvania.
51. Nippo Sangyo Co., Ltd. *Product Guide, Circular Texture Meter, ASTM E-2157-01*. http://www.nippou.com/en/products/ct.html. Accessed March 23, 2006.
52. Saito, K., T. Horiguchi, A. Kasahara, H. Abe, and J. J. Henry. Development of Portable Tester for Measuring Skid Resistance and Its Speed Dependency on Pavement Surfaces. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 1536, Transportation Research Board of the National Academies, Washington, D.C., 1996, pp. 45–51.
53. ASTM Standard E1911. *Standard Test Method for Measuring Paved Surface Frictional Properties Using the Dynamic Friction Tester*. ASTM International, West Conshohocken, Pennsylvania.
54. Henry, J. J., H. Abe, S. Kameyama, A. Tamai, A. Kasahara, and K. Saito. *Determination of the International Friction Index (IFI) Using the Circular Texture Meter (CTM) and the Dynamic Friction Tester (DFT)*. Publication No. 109.01.06.B-2000. Permanent International Association of Road Congresses (PIARC), Nantes, France, 2000.
55. Kowalski, K. J., R. S. McDaniel, and J. Olek. *Identification of Laboratory Technique to Optimize Superpave HMA Surface Friction Characteristics*. Publication FHWA/IN/JTRP-2010/06, Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2010. doi: 10.5703/1288284314265.
56. McDaniel, R. S., K. J. Kowalski, and A. Shah. *Evaluation of Reclaimed Asphalt Pavement for Surface Mixtures*. Publication FHWA/IN/JTRP-2012/03. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2012. 10.5703/1288284314665.
57. Kowalski, K. J., R. S. McDaniel, and J. Olek. Development of a Laboratory Procedure to Evaluate the Influence of Aggregate Type and Mixture Proportions on the Frictional Characteristics of Flexible Pavements. *Journal of the Association of Asphalt Paving Technologists*, Vol. 77, 2008, pp. 35–70.
58. Kowalski, K. J., R. S. McDaniel, J. Olek, A. Shah, and S. Li. Development of the International Friction Index Flag Value. Paper No. 705, presented at the Tenth International Conference on Application of Advanced Technologies in Transportation, Athens, Greece, May 27–31, 2008.

APPENDIX B
EXPERIMENTAL DESIGN, MATERIALS AND MIX DESIGNS

This appendix describes the experimental designs, materials and mix designs used in the various parts of this project.

EXPERIMENTAL DESIGNS

The first part of this project involved evaluating the effects of increasing amounts of polish susceptible coarse aggregates in dense graded (DGA) and stone matrix asphalt (SMA) mixtures. Initially, the plan was to evaluate three different polish susceptible coarse aggregates blended with three different polish resistant aggregates—steel furnace slag (SF), air-cooled blast furnace slag (ACBF) and sandstone (SStn). This was later modified to include only two polish susceptible coarse aggregates with the addition of testing materials from the Polish Resistant Aggregate (PRA) field trial on SR 62. The two polish susceptible coarse aggregates (PSI and PSII) were blended with the three polish resistant aggregates at contents ranging from 0% to 40%. The SR62 materials were tested at their design levels. The final experimental design for the coarse aggregate study is shown in Tables B.1 for the DGA and B.2 for the SMA. (The SR62 mixes will be detailed separately.) A total of 13 DGA mixes and nine SMA mixes were tested.

For the study of the SR62 materials, samples of three field fabricated mixtures were provided to the NCSC by the OMM. These mixes were those used in the field trial and consisted of one mix with slag coarse aggregate only, one with PRA coarse aggregate only and one with a blend of slag and PRA. Since the gradations of these mixes varied from that used in the past at the NCSC, another mixture was prepared in the laboratory using the PRA aggregate but blended to match the “lab standard” gradation used previously in order to explore the impact of the mix gradation on the laboratory polishing and testing; this sample is labeled PRA_Lab to distinguish it from PRA_Field. Thus, four mixes were evaluated in this part of the study.

Lastly, nine additional mixtures were tested in the fine aggregate portion of the project. Mixtures tested here included the same three polish resistant aggregates—steel furnace slag, air cooled blast furnace slag and sandstone—blended with a polish susceptible fine aggregate at 0%, 10% and 20%, as shown in Table B.3.

MATERIALS AND MIX DESIGNS

The aggregate components were obtained by INDOT either from the aggregate sources or from hot mix contractors’ plants. The steel slag, limestones (PSI and PSII) and PRA aggregate were obtained in southern Indiana. The air cooled blast furnace slag was obtained from the source in northern Indiana, and the sandstone was from a source in southern Illinois. One natural sand was used in the coarse aggregate portion of the study in both the DGA and SMA mixes; it was obtained from a contractor in southern Indiana. Lastly, bag house fines sampled at a local hot mix plant were used in the SMA mixes.

Example mix designs were provided by some of the contractors whose materials were used in the study. These were used as starting points for the mix designs, which were then recreated and modified or verified in the NCSC lab. The goal of the mix designs was to keep the gradations consistent while changing the percentages of different types of aggregates and meeting the desired aggregate contents. All of the mixes studied were 9.5 mm mixes. The gradations and binders contents for the various mixtures studied are shown in Tables B.4 through B.7 and are illustrated graphically in Figures B.1 through B.11.

One PG64-22 binder was used in all of the mixtures, although this grade is not typically used in SMAs in Indiana. Since this was an aggregate friction study, not a mixture performance study, the use of a binder that would wear away fairly quickly during polishing was preferred. The binder content in the different mixtures varied to account for changes in the aggregate absorption.

REFERENCES

1. AASHTO M325. *Standard Specification for Stone Matrix Asphalt (SMA)*. Association of State Highway and Transportation Officials.

TABLE B.1
Dense Graded Mixes Evaluated in Coarse Aggregate Test Matrix

	Polish Susceptible Content						
Aggregate Components	**0%**	**10%**	**20%**	**20%**	**25%**	**30%**	**40%**
Polish Susceptible Aggregate	—	PSI	PSI	PSII	PSII	PSI	PSI
Steel Furnace Slag(SF)	X	X	X	X	X	X	X
Air Cooled Blast Furnace Slag(ACBF)	X		X			X	
Sandstone(SStn)	X		X			X	

TABLE B.2
SMA Mixes Evaluated in Coarse Aggregate Test Matrix

	Polish Susceptible Content				
Aggregate Components	**0%**	**10%**	**20%**	**20%**	**40%**
Polish Susceptible Aggregate	—	PSII	PSI	PSII	PSII
Steel Furnace Slag(SF)	X	X	X	X	X
Air Cooled Blast Furnace Slag(ACBF)	X			X	
Sandstone(SStn)	X			X	

TABLE B.3
Fine Aggregate Study Test Matrix

	Polish Susceptible Fine Aggregate Content		
Aggregate Components	**0%**	**10%**	**20%**
Steel Furnace Slag(SF)	X	X	X
Air Cooled Blast Furnace Slag(ACBF)	X	X	X
Sandstone(SStn)	X	X	X

TABLE B.4

Gradations and Binder Contents of DGA Mixes in Coarse Aggregate Study

Sieve Size	PS-0			PSI-10	PSI-20			PSII-20	PSI-25	PSI-30			PSI-40	Target
(mm)	SF	ACBF	SStn	SF	SF	ACBF	SStn	SF	SF	SF	ACBF	SStn	SF	All Blends
12.5	100.0	100.0	100.0	100.0	100.0	99.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
9.5	89.9	92.5	95.3	90.4	90.9	91.8	94.5	91.2	91.2	91.5	92.8	94.1	92.0	93.5
4.75	44.2	53.9	58.8	45.7	47.2	53.4	57.1	47.9	48.5	49.4	54.1	56.3	50.5	53.0
2.36	37.3	44.7	43.9	38.2	39.1	43.6	43.8	39.6	40.0	40.5	44.0	43.7	40.9	42.0
1.18	31.0	37.2	35.5	31.8	32.5	36.4	35.8	32.4	3.3	33.7	36.7	35.9	34.0	34.0
0.600	18.4	21.9	20.5	18.9	19.3	21.4	20.8	19.2	19.7	20.0	21.6	21.0	20.2	20.5
0.300	5.0	5.5	4.6	5.1	5.2	5.5	5.0	5.1	5.3	5.3	5.6	5.1	5.4	5.2
0.150	2.7	2.6	1.8	2.7	2.7	2.0	2.2	2.6	2.7	2.7	2.1	2.4	2.8	2.5
0.075	2.2	2.0	1.0	2.2	2.1	1.6	1.4	2.1	2.1	2.1	1.6	1.6	2.1	2.1
AC%	4.7	6.8	5.6	4.8	4.8	6.6	5.7	4.8	5.8	5.8	6.3	5.8	4.8	4.0% Air

TABLE B.5

Gradations and Binder Contents of SMA Mixes in Coarse Aggregate Study

	PS-0			PSII-10	PSI-20	PSII-20			PSI-40	Target
Sieve Size (mm)	SF	ACBF	STN	SF	SF	SF	ACBF	STN	SF	All Blends
12.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100
9.5	85.8	85.8	87.0	83.8	84.2	84.2	86.0	86.4	85.0	85
4.75	31.2	32.6	40.4	30.9	30.2	30.2	33.0	39.1	31.6	34
2.36	21.8	22.1	21.8	21.8	21.7	21.7	22.0	22.2	21.7	22
1.18	19.4	19.9	18.1	19.5	19.5	19.5	19.9	18.9	19.6	18
0.600	16.2	16.6	14.8	16.3	16.3	16.3	16.5	15.5	16.4	16
0.300	12.2	12.3	10.8	12.3	12.3	12.3	12.4	11.4	12.4	12
0.150	10.4	10.3	9.0	10.4	10.4	10.4	10.4	9.5	10.5	10
0.075	10.0	9.9	8.1	10.0	10.0	10.0	9.9	8.7	10.0	9.5
AC%	5.8	7.1	5.7	5.9	5.9	5.9	6.9	5.8	6.0	4.0% Air

NOTE: SMA gradations by volume because Gsb of individual stockpiles varies by more than 0.2 in accordance with AASHTO M325 *(1)*.

TABLE B.6

Gradations, RAP and Binder Contents of SR62 Mixes

Sieve Size (mm)	Slag	Slag_PRA	PRA_Field	PRA_Lab
19.0	100.0	100.0	100.0	100.0
12.5	97.0	97.0	94.9	100.0
9.5	87.0	89.6	87.3	94.0
4.75	60.0	62.0	61.9	52.0
2.36	45.0	45.0	37.9	41.8
1.18	32.0	31.0	23.8	34.0
0.600	20.0	20.0	15.6	24.6
0.300	9.0	9.0	10.0	8.4
0.150	5.0	6.0	7.2	4.1
0.075	3.6	4.3	6.1	2.5
RAP in mix(weight %)	15.0	14.7	5.6	0
RAP Binder Replacement %	18.2	15.0	6.6	0
Virgin Binder %	3.4	4.3	5.5	5.8
Extracted Binder %	3.9	4.7	5.7	--

-- Not extracted.

TABLE B.7
Gradations and Binder Contents of Mixes in Fine Aggregate Study

Sieve Size (mm)	PS0-SF	PS0-ACBF	PS0-SStn	PS10-SF	PS10-ACBF	PS10-SStn	PS20-SF	PS20-ACBF	PS20-SStn	Target
12.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
9.5	92.2	93.2	94.5	93.8	94.6	94.7	93.8	94.6	94.7	93.5
4.75	51.9	54.4	53.5	54.1	52.0	52.2	53.7	52.0	52.2	53.0
2.36	41.1	42.9	43.1	40.6	43.0	41.3	42.8	43.0	41.3	42.0
1.18	33.4	35.4	35.1	32.6	33.4	32.6	34.3	33.4	32.6	34.0
0.600	21.0	20.4	20.6	19.2	20.9	21.3	19.8	20.9	21.3	20.5
0.300	5.0	5.6	4.6	6.6	5.6	6.4	5.7	5.6	6.4	5.2
0.150	2.7	2.0	1.8	2.7	2.7	1.9	2.8	2.7	1.9	2.5
0.075	2.2	1.6	1.0	2.3	2.1	1.1	2.3	2.1	1.1	2.1
AC%	5.5	6.8	5.8	5.5	6.1	5.1	5.4	5.7	4.3	4.0% Air

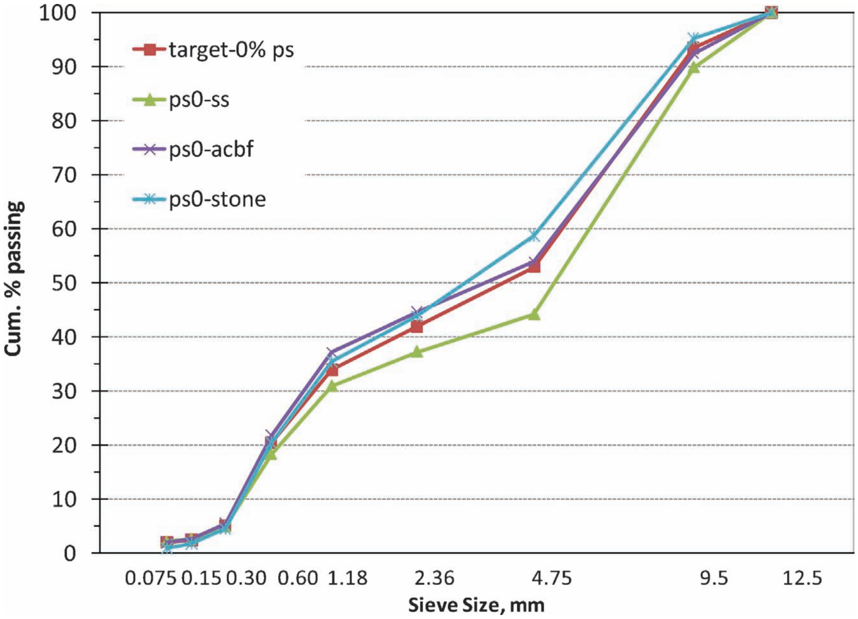

Figure B.1 Gradations of DGA mixes in coarse aggregate study with 0% polish susceptible stone.

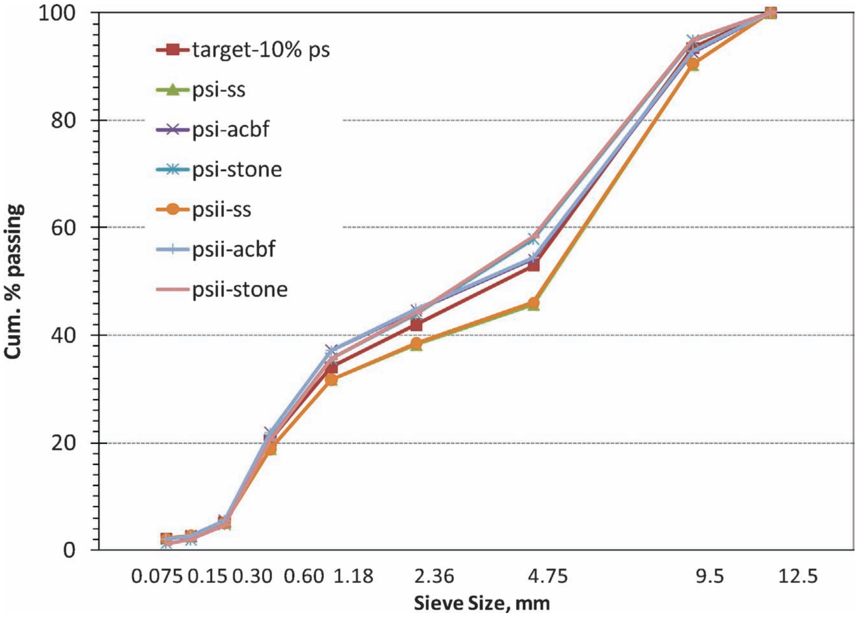

Figure B.2 Gradations of DGA mixes in coarse aggregate study with 10% polish susceptible stone.

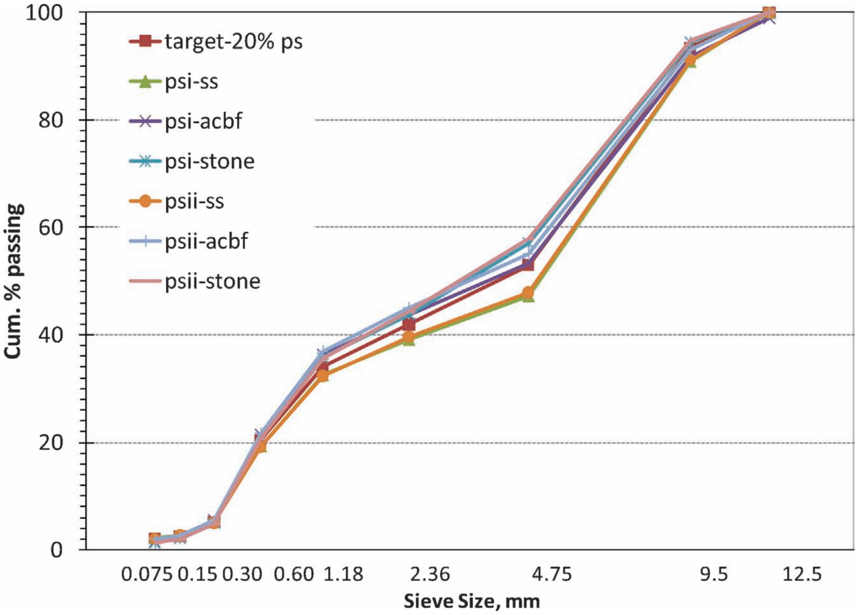

Figure B.3 Gradations of DGA mixes in coarse aggregate study with 20% polish susceptible stone.

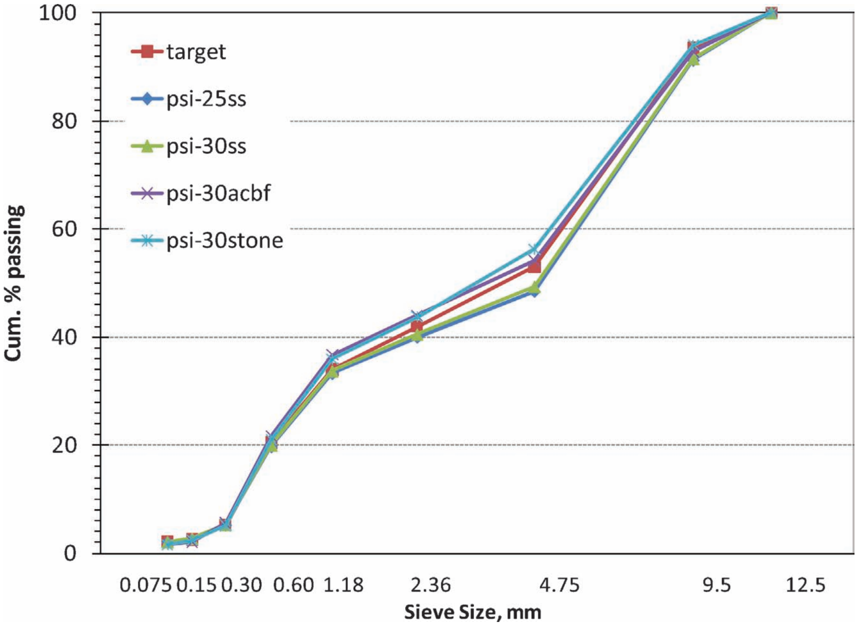

Figure B.4 Gradations of DGA mixes in coarse aggregate study with 25% and 30% polish susceptible stone.

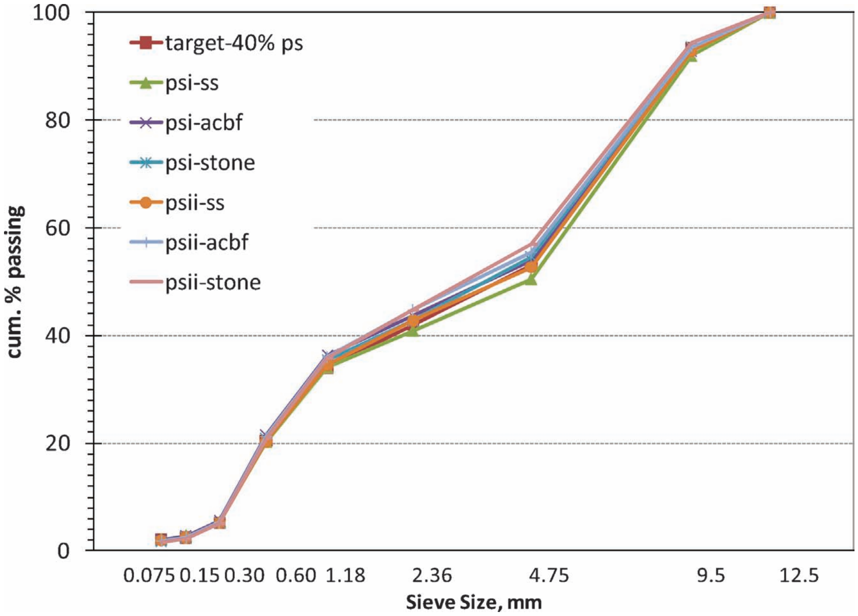

Figure B.5 Gradations of DGA mixes in coarse aggregate study with 40% polish susceptible stone.

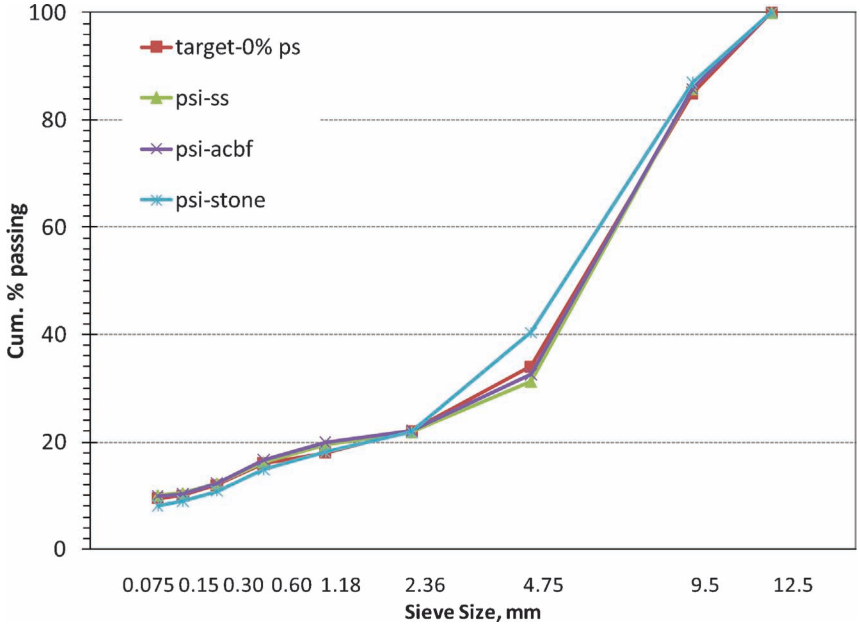

Figure B.6 Gradations of SMA mixes with 0% polish susceptible aggregate.

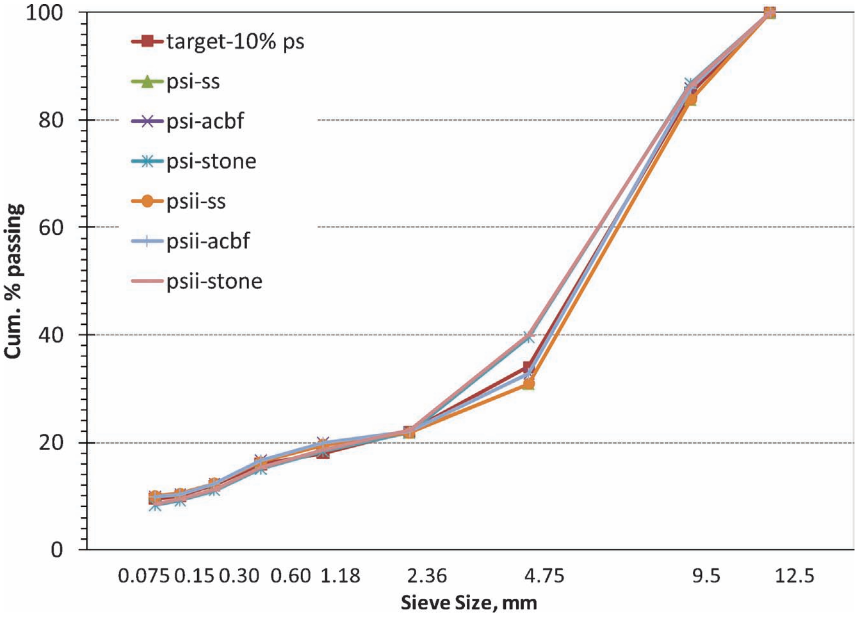

Figure B.7 Gradations of SMA mixes with 10% polish susceptible aggregate.

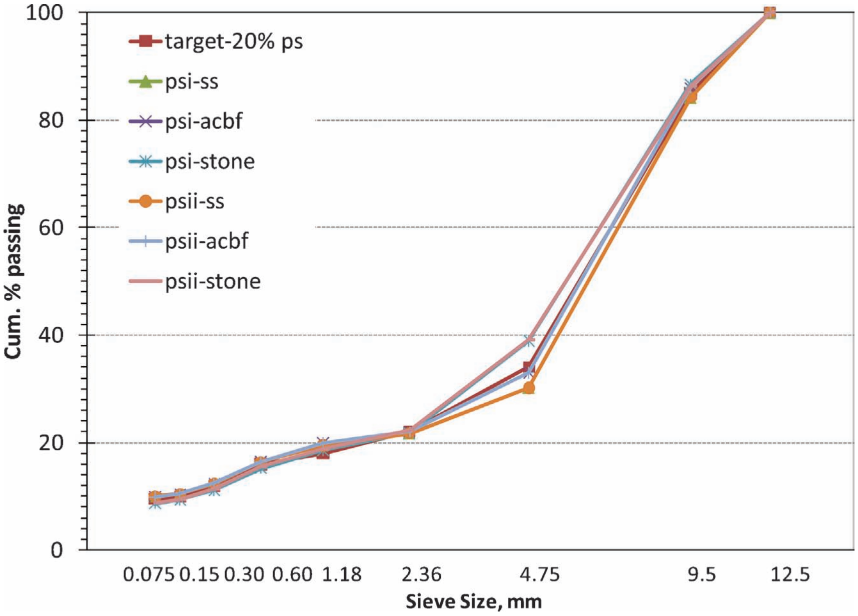

Figure B.8 Gradations of SMA mixes with 20% polish susceptible aggregate.

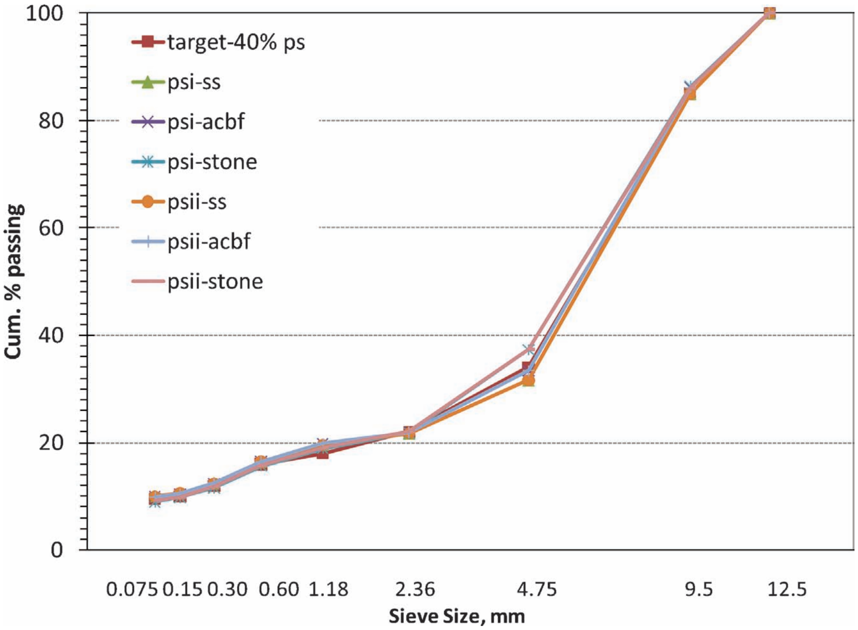

Figure B.9 Gradations of SMA mixes with 40% polish susceptible aggregate.

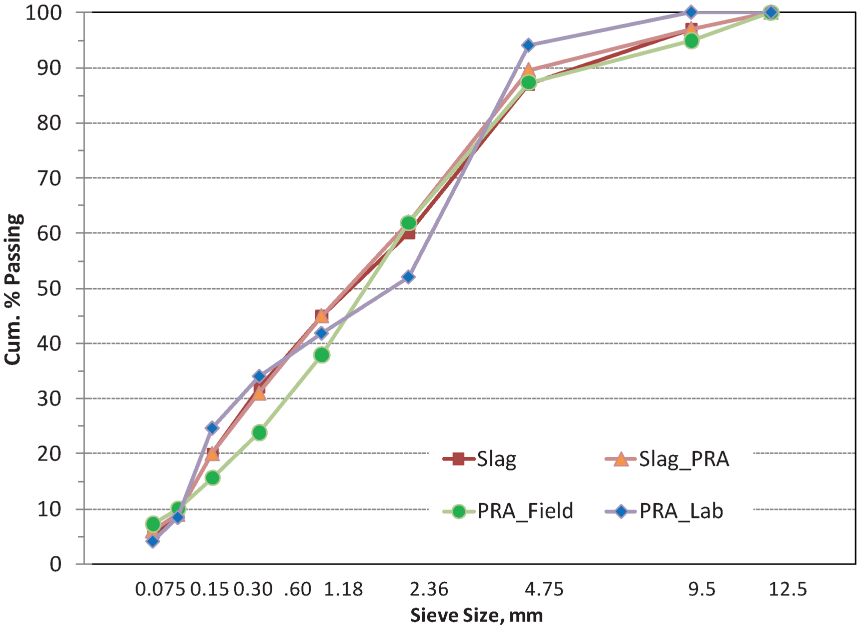

Figure B.10 Gradations of SR62 mixtures.

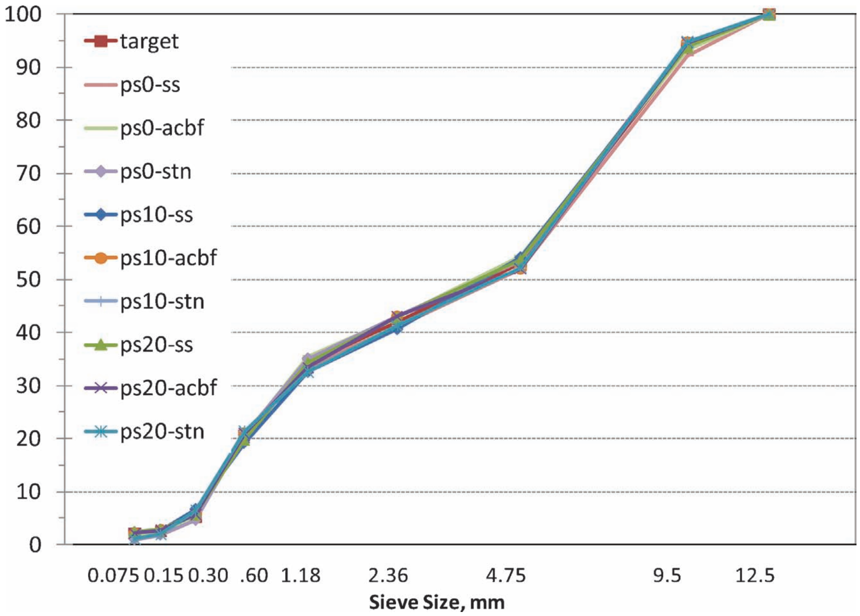

Figure B.11 Gradations of mixes in fine aggregate study.

APPENDIX C
FRICTION TESTING PROCEDURES

In order to determine the frictional properties of the various mixtures, a test procedure developed in another study, *Identification of Laboratory Technique to Optimize Superpave HMA Surface Friction Characteristics* (JTRP Report No. FHWA/IN/JTRP-2010/6) *(1)*, was utilized. This procedure is briefly described here.

First, slabs are fabricated from the mixture to be tested. Laboratory produced HMAs are reheated to the compaction temperature. Based on the volume of the mold and the specific gravity of the mix, the approximate weight of mix that would yield 7% to 8% air voids (V_a) is determined. That amount of mix is then placed in a square wooden mold (500 mm [20 in] by 500 mm [20 in] and 38 mm [1.5 in] deep) and compacted using a large "rolling pin" mounted on a fork lift. Once compacted, the slabs are allowed to cool thoroughly.

Following compaction, the slabs are subjected to polishing and their frictional properties are periodically measured. Polishing is performed using a device called a Circular Track Polishing Machine (CTPM), shown in Figure C.1. This device consists of three rubber tires attached to a rotating plate. The wheels travel over the same footprint as that of the devices used to measure friction and texture (described below). The polishing wheels travel at approximately 47 revolutions per minutes (RPMs). Since each revolution rotates three tires over the same track on the surface, there are about 141 wheel passes per minute. Water is sprayed on the slab surface to help remove the debris generated during polishing. During polishing, a total load of 0.65 kN (150 lbs.) is applied through the tires to the surface.

Before polishing is initiated and periodically during polishing, the surface texture and friction of the slabs are measured. The surface texture is measured using a laser-based Circular Track Meter (CTM), following ASTM E2157 *(2)*. The texture is reported in terms of the Mean Profile Depth (MPD) and measured in millimeters. Then, the friction of the surface is measured using a Dynamic Friction Tester (DFT), following ASTM E1911 *(3)*. In the DFT device, three rubber sliders attached to the disk are accelerated to tangential velocities of up 90 km/h (56 mph) and then dropped onto the wet surface. The torque generated as the disk slows provides an indication of the friction at various speeds. The main value of interest here is the DFT number at 20 km/h (12 mph), designated DF_{20}. The previously determined MPD value can be combined with the DF20 value and used to calculate the International Friction Index (IFI) following ASTM E1960 *(4)*. The IFI consists of two parameters: the calibrated wet friction at 60 km/h (F60) and the speed constant of wet pavement friction (S_p).

Figure C.1 Circular Track Polishing Machine.

The polisher is stopped periodically during testing so the measurement of friction and texture can be performed. In this study, this was done after the following cumulative numbers (in thousands) of wheel passes: 1.5, 3.6, 9, 18, 30, 45, 75, 120 and 165.

Typically, for asphalt mixtures the initial friction tends to be low because of the presence of binder film coating the aggregate particles. After the binder film is worn off by traffic, the friction increases rapidly. Continued wheel passes tend to cause a decrease in the friction level, and sometimes changes in the texture, as the aggregate particles undergo polishing and sometimes are dislodged (ravel). Eventually, the friction tends to level off at the so-called terminal friction value. This occurs when embedded aggregates at the surface are polished as much as they will polish and further wheel passes do not cause additional loss of friction. This general trend in friction is observed both in the field and in the lab. Past research work has shown that terminal friction can usually be obtained in the CTPM after fewer than 165,000 wheel passes (55,000 CTPM revolutions), even for mixtures with high friction aggregates like steel slag.

In addition to the MPD, the DF_{20} parameter is also determined after each increment of polishing cycles. These two parameters are used to calculate the calibrated wet friction (F60) values (following the ASTM E1960 *(4)*), as shown below:

$$F60 = 0.81 + 0.732 DF_{20} e^{\frac{-40}{Sp}} \qquad (1)$$

$$S_p = 14.2 + 89.7 MPD \qquad (2)$$

where: DF_{20} = wet friction number measured at 20 km/h
MPD = mean profile depth (mm).

When using Equation 1 with the typical range of MPD values (0.3 mm to 1.7 mm) and DF_{20} values (0.3 to 0.7), it can be noted that the F60 parameter is highly influenced by the DF_{20}. The trend of the plot of DF_{20} versus number of wheel passes is typically similar to the plot of F60 versus number of wheel passes. An example of the typical changes in the DF_{20} values taking place during polishing is shown in Figure C.2. The corresponding profile depth data is shown in Figure C.3, and the resultant F60 results are shown in Figure C.4. This illustrates the great impact of the DF_{20} data on the F60 values.

In nearly all cases, the polishing action of the CTPM causes an increase in the texture depth of the slabs. Some increases in texture have also been observed in the field, but when excessive increases occur in the lab, they can affect the interpretation of the results.

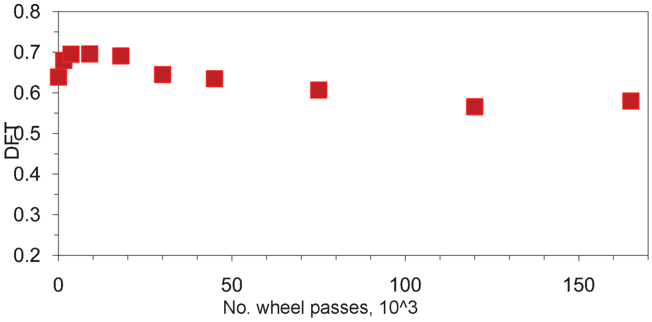

Figure C.2 Example of typical dynamic friction (DF_{20}) data.

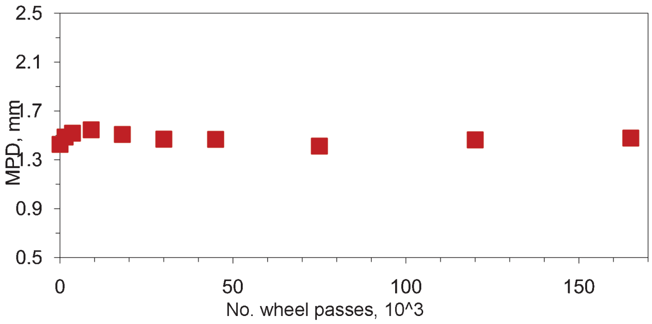

Figure C.3 Example of typical mean profile depth (MPD) data.

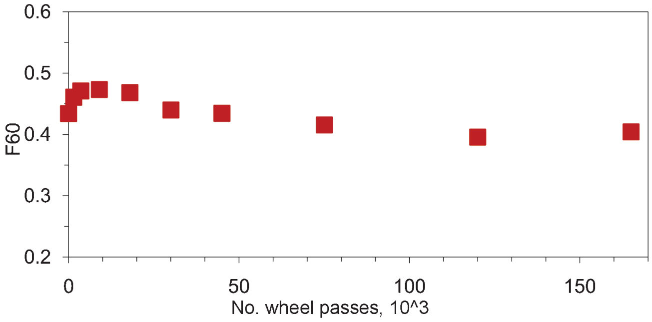

Figure C.4 Example of typical F60 data.

An increase in MPD can lead to an inflation of the F60 value. It is obvious that the increase in texture is caused by some loss of particles at the surface. The reasons why some slabs experience more increase in texture than others is not as obvious. It may be because of mix design issues (inadequate binder or poor gradations) or poor compaction of the slabs. For some mixes, the polishing action seems to be too severe; additional research is needed to explore this issue and attempt to resolve it.

RECALIBRATION OF THE DFT

During a concurrent study, problems developed with the DFT and service was required. After servicing, the device was recalibrated by the DFT technician. When the DFT was returned to the NCSC and testing resumed, a marked difference in the DFT readings was noted. Unfortunately, despite being asked to take readings on slabs before and after servicing without applying additional polishing passes, the technician assisting at the time did not do so. Consequently, another way to relate the readings before and after servicing was required.

In support of other studies, periodic testing of the INDOT Test Track was performed with the CTM and DFT to allow correlation of those devices with the towed friction trailer. CTM and DFT readings were taken on the same day that the towed friction trailer calibration was checked. While these values show seasonal variation from one set of readings to another, since the CTM/DFT readings were taken on the same day as the towed friction trailer, these differences can be ignored. Readings were taken on the asphalt section, the tined concrete and the slick concrete to allow comparison over a range of friction levels. In addition, tests were conducted with both the rib and smooth tires on the towed friction trailer.

In order to relate the DFT readings taken before and after servicing, then, the CTM and the serviced DFT were used to test the track in August 2011, and these readings were compared to the towed friction trailer data. This comparison showed that the DFT values changed by a differing amount depending on the level of friction. On the slick concrete section, which provides very low friction, the change in DFT value was around 0.11. On the tined concrete, which provides a high level of friction, the change was about 0.40. On the asphalt section, which provides an intermediate level of friction, the change in DFT values was also intermediate—around 0.20. The DFT readings after servicing were lower than before servicing.

In previous research, the test track and other field data was used to estimate an F60 friction flag value related to the flag value used by INDOT with the towed friction trailer data. An F60 value of about 0.20 when terminal polish is reached is believed to be a relatively conservative friction flag value that can be used to evaluate mixes in the lab or field when tested with the CTM and DFT. Typically the terminal friction value is reached within 165,000 wheel passes, even with high friction aggregates like steel slag. In some cases in this study, however, additional wheel passes

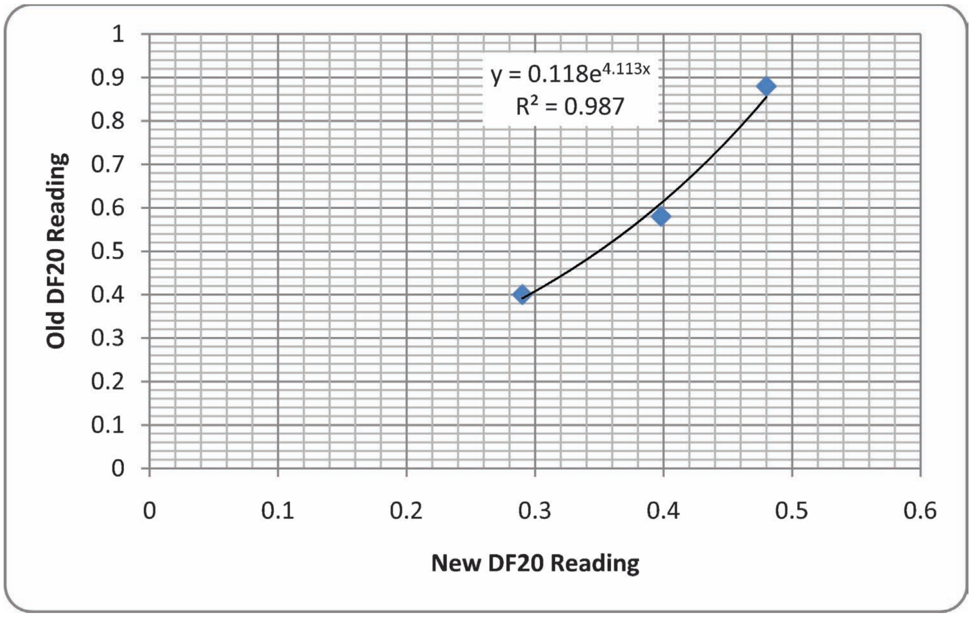

Figure C.5 Shift factor to correct DFT readings taken after repair of equipment.

were applied if it was questionable whether terminal friction had been reached or not. Unfortunately, these additional passes were applied after recalibration, so they appear to show a decrease in friction which may or may not be accurate.

Since the friction flag value was established before problems developed with the DFT, it was determined that the readings in the present study taken after servicing should be "corrected" to the readings before servicing. So, the DFT readings taken in the present study after recalibration will be corrected by a shift factor that will increase them to be comparable with the readings taken before servicing. Figure C.5 shows the pre-servicing DFT readings versus the post-servicing DFT readings. The best fitting trend line (giving the highest R-squared value) is an exponential line. Therefore, an exponential shift factor corresponding to the measured DFT value will be used to give a "corrected" DFT value similar to those measured before the repair.

All of the DGA slabs with 0%, 20% and 40% local aggregate were tested to 165,000 wheel passes before servicing of the DFT. The additional readings beyond 165,000 wheel passes were made after the recalibration and consequently needed adjustment. In addition, all of the testing of the DGA slabs with 25% and 30% RAP was conducted after the recalibration. Similarly, the SMA slabs were all tested to 165,000 wheel passes before recalibration but additional passes were applied after. The SR62 slabs with slag and slag+PRA were tested to 165,000 wheel passes before recalibration, but the additional wheel passes and samples with PRA only (both lab and field) were tested after recalibration. All of the Fine Aggregate slabs were tested after recalibration.

The newly calibrated equipment is very likely giving correct readings now but the flag value to which we compare the readings was developed before the recalibration of the equipment. The "corrected" readings compare well to previous measurements, giving some confidence that the adjustment is reasonable. Future research should be proposed to refine the laboratory friction testing and polishing protocol. Topics to be addressed in that research could include equipment calibration, reevaluation of the flag values, improved slab compaction procedures and improvements to the polishing procedures (such as looking at different downward forces to reduce the tendency to cause raveling of the surfaces).

REFERENCES

1. McDaniel, R. S., H. Soleymani, and A. Shah. *Use of Reclaimed Asphalt Pavement (RAP) Under Superpave Specifications: A Regional Pooled Fund Project*. Publication FHWA/IN/JTRP-2002/6. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2002. doi: 10.5703/1288284313465.
2. ASTM Standard E2157. *Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter*. ASTM International, West Conshohocken, Pennsylvania.
3. ASTM Standard E1911. *Standard Test Method for Measuring Paved Surface Frictional Properties Using the Dynamic Friction Tester*. ASTM International, West Conshohocken, Pennsylvania.
4. ASTM Standard E1960. *Standard Practice for Calculating International Friction Index of a Pavement Surface*. ASTM International, West Conshohocken, Pennsylvania.

APPENDIX D
POLISHING AND TESTING RESULTS

The friction (DF_{20}) and texture depth (MPD) results are shown graphically for the tested mixtures below, followed by the calculated F60 results. Brief discussion and interpretation of the results accompany each set of graphs. In the following graphs, a vertical dotted line indicates when the DFT recalibration occurred. An asterisk after the data label in the legend indicates that all of that data was collected after the DFT was recalibrated, so the dotted vertical line applies only to data without the asterisk in its legend. The heavy horizontal line at F60 = 0.20 signifies the estimated friction flag value.

COARSE AGGREGATE STUDY—HMA MIXES

The following three graphs compare the three high friction aggregates with no local aggregate, that is, the control mixes. Figure D.1 shows the DF_{20} values versus wheel passes, Figure D.2 shows the mean profile depths and Figure D.3 shows the resulting F60 values. The steel slag mix tends to have higher DF_{20} values from about 30,000 to 75,000 wheel passes. However, the values at 165,000 wheel passes—the usual stopping point—are comparable for the steel and ACBF slags and are slightly higher than for the sandstone. Additional wheel passes were applied to the ACBF and sandstone mixes after recalibration of the DFT because it was perhaps questionable whether these two mixes had reached their terminal friction levels; the results from 75,000 to 165,000 wheel passes varied somewhat. The additional wheel passes appeared lower even after adjusting for the calibration difference. It is unclear whether this is because of additional polishing or whether the correction factor is inadequate. In either case, the resulting F60 value, shown in Figure D.3, is well above the friction flag value. The mean profile depths in Figure D.2 show a gradual increase; this is often seen as some particles may be lost (ravel) during polishing. Substantial raveling was not observed.

Figures D.4 through D.6 show the results of testing the DGA mixes with air cooled blast furnace slag and varying amounts of polish susceptible PSI. Figure D.4 shows that increasing the

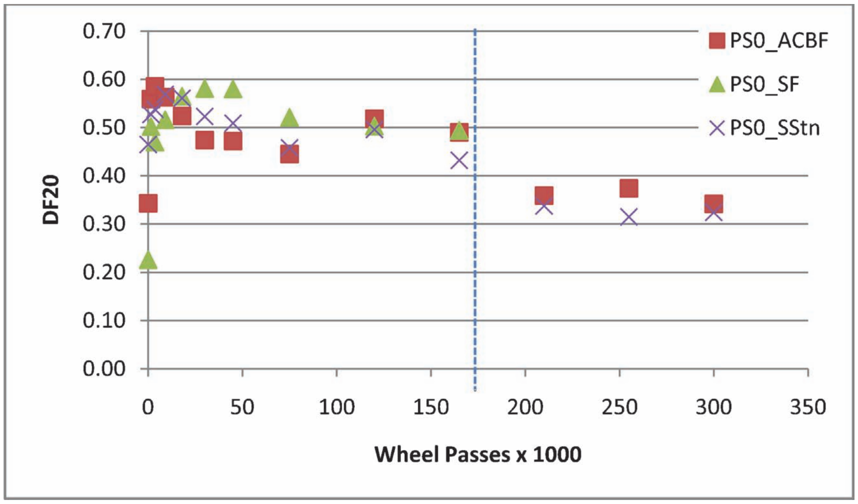

Figure D.1 DF_{20} Results for DGA mixes with 0% local aggregate.

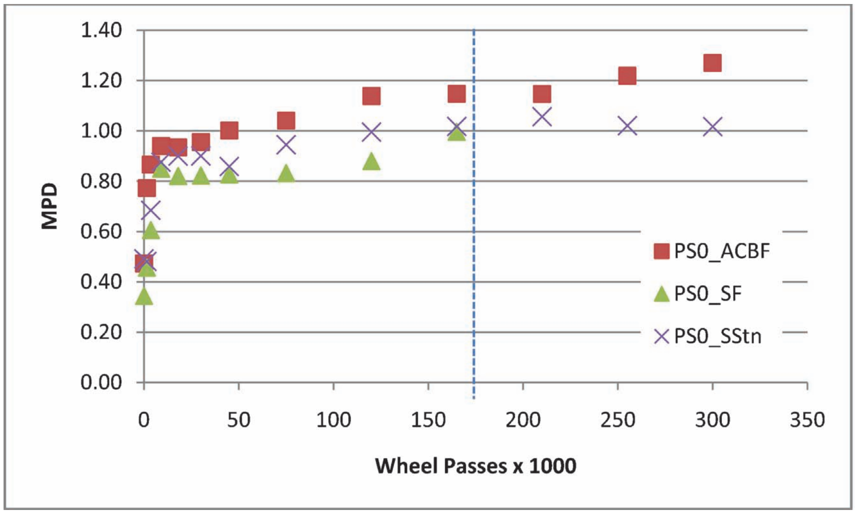

Figure D.2 MPD Results for DGA mixes with 0% local aggregate.

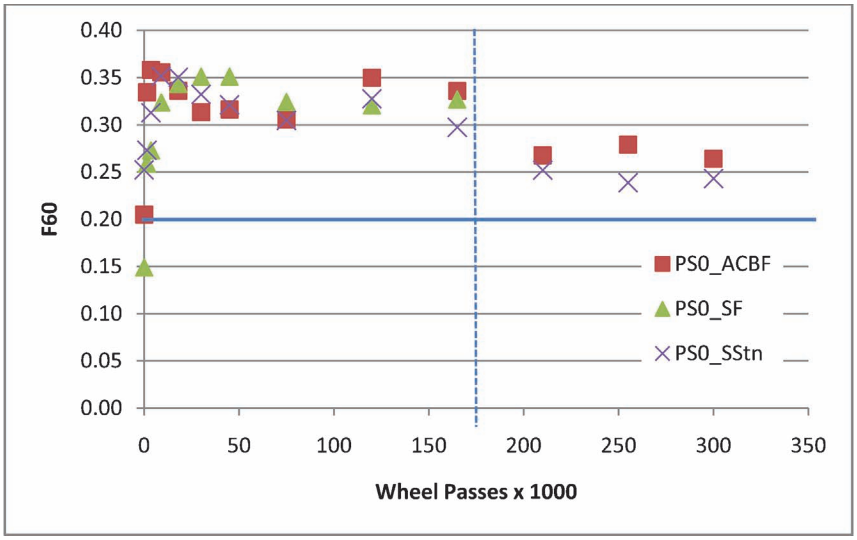

Figure D.3 F60 Results for DGA mixes with 0% local aggregate.

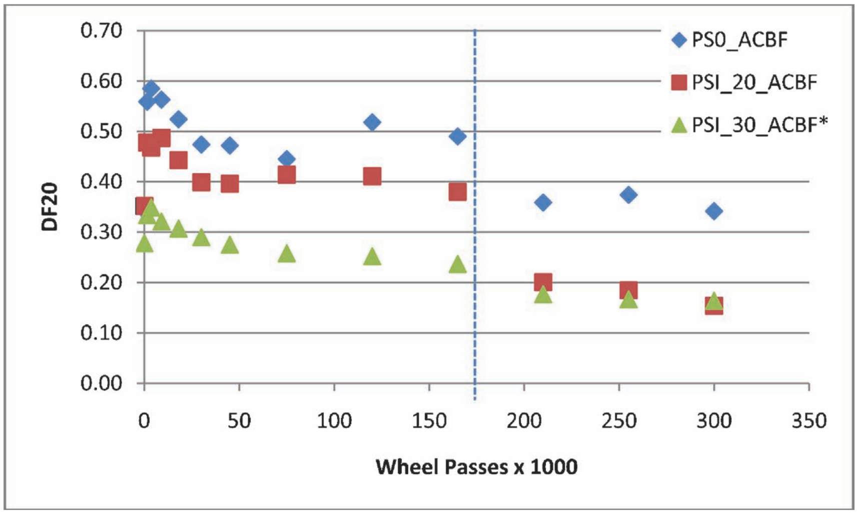

Figure D.4 DF_{20} results for DGA mixes with ACBF and varying amounts of polish susceptible coarse aggregate.

amount of polish susceptible coarse aggregate decreases the DF_{20} value. Figure D.5 suggests that the 0% and 30% local aggregate mixes exhibited greater increases in texture depth than the 20% mixture, but none of these increases are excessive, compared to previous testing, and undue raveling was not observed visually.

Figure D.6 also reflects the decrease in friction as the local aggregate content increases. After 165,000 wheel passes, the control mix has the highest F60 value, followed by the mix with 20% PSI; both of these F60 values are well above the friction flag value. The mix with 30% local aggregate is approaching the flag value at 165,000 passes. When additional passes were applied after recalibration of the DFT, the same trends continued but the F60 value was lower, even after the correction factor was applied.

The next set of figures, D.7 through D.9, summarize the results of testing the DGA mixes with steel furnace slag and varying amounts of polish susceptible coarse aggregate. As with the previous set of results on the ACBF mixes, increasing the percentage of local aggregate again led to a decrease in the friction values, both DF_{20} and F60, as shown in Figures D.7 and D.9 respectively. Figure D.8 shows that the MPD of the mixes with steel furnace slag contents greater than 25% were slightly higher than the lower slag content mixes. At 165,000 wheel passes, there is little difference between the mixes with 10% and 20% PSI. Similarly, the mixes with 25 and 30% PSI are comparable; those two mixes still appear to be above the friction flag value while the mix with 40% PSI is approaching the flag value. Additional wheel passes were applied to the mixes with 10, 20, 25 and 30% PSI; while the F60 values were lower, the trends were the same. At 310,000 passes, the F60 value of the 25% PSI mix was just above the flag value and the 30% mix was below; it must be remembered, however, that the flag value was estimated based on results at 165,000 wheel passes.

Three quantities of PSI with sandstone were investigated, 0%, 20% and 30%; the results are shown in Figures D.10 through D.12. Up to 165,000 wheel passes, the control and 20% mixes are providing higher friction values than the 30% mix, which was approaching the F60 friction flag value. In addition, the 30% mix exhibited a high increase in the texture depth, as shown in Figure D.11. This increase in macrotexture would have artificially increased the F60 value, so had the mix not raveled so much, the

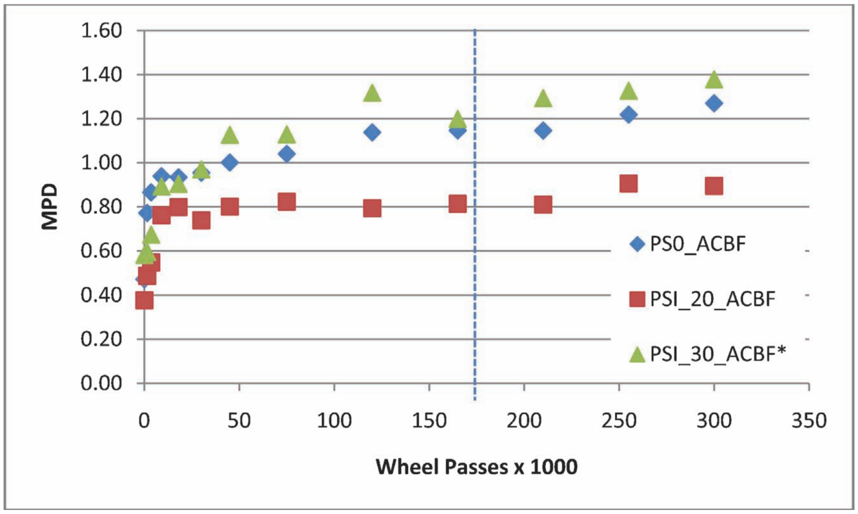

Figure D.5 MPD results for DGA mixes with ACBF and varying amounts of polish susceptible coarse aggregate.

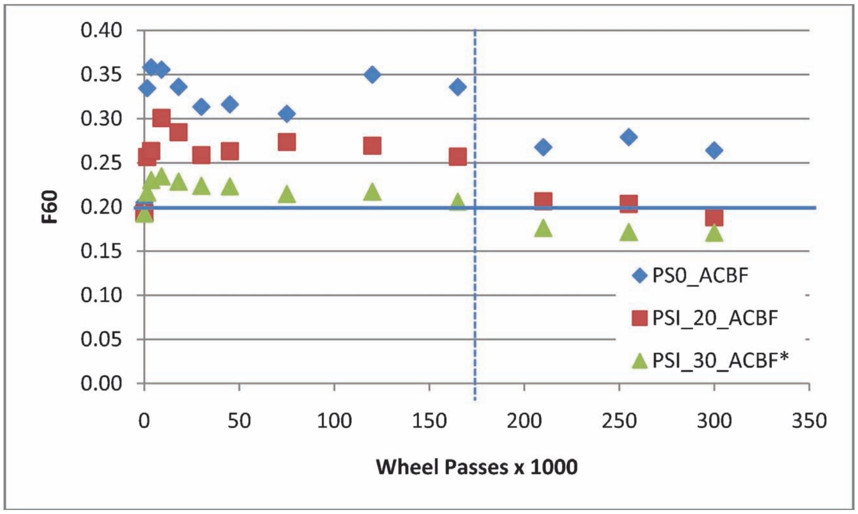

Figure D.6 F60 results for DGA mixes with ACBF and varying amounts of polish susceptible coarse aggregate.

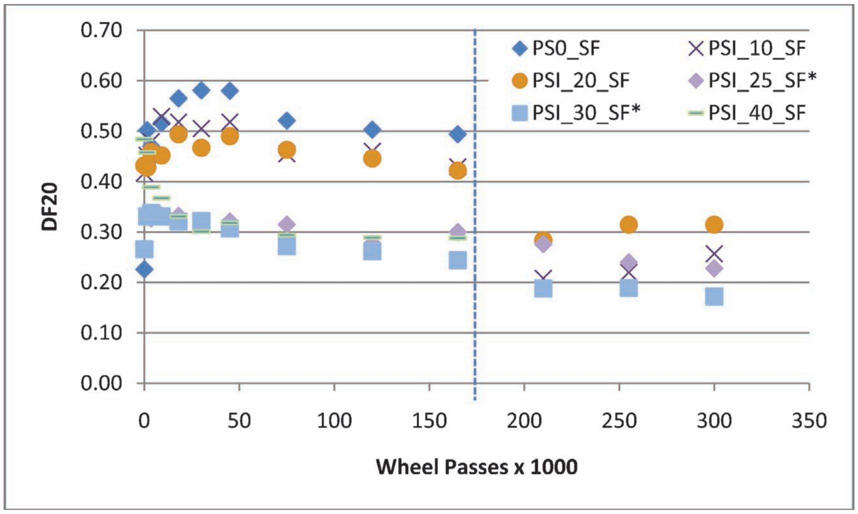

Figure D.7 DF_{20} results for DGA mixes with steel slag and varying amounts of polish susceptible coarse aggregate.

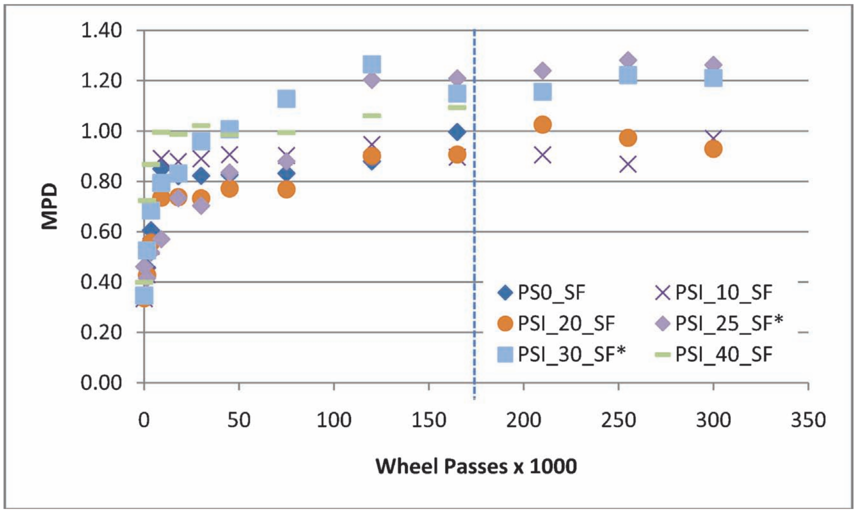

Figure D.8 MPD results for DGA mixes with steel slag and varying amounts of polish susceptible coarse aggregate.

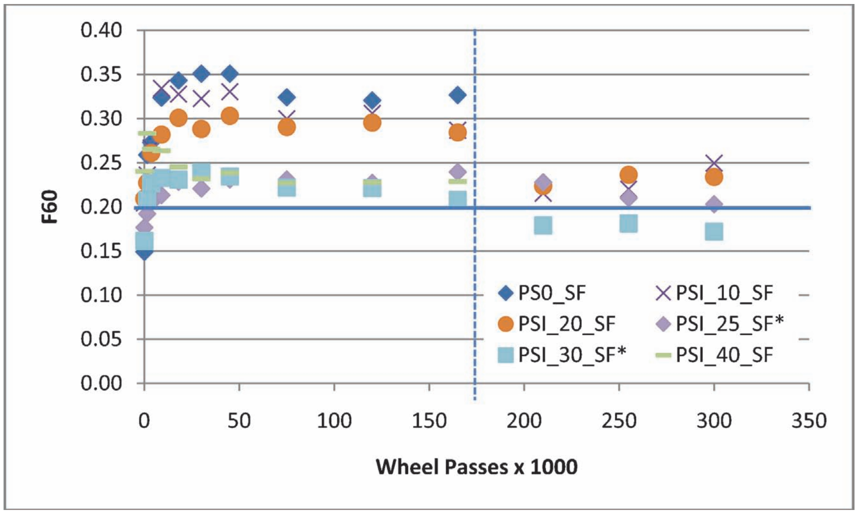

Figure D.9 F60 results for DGA mixes with steel slag and varying amounts of polish susceptible coarse aggregate.

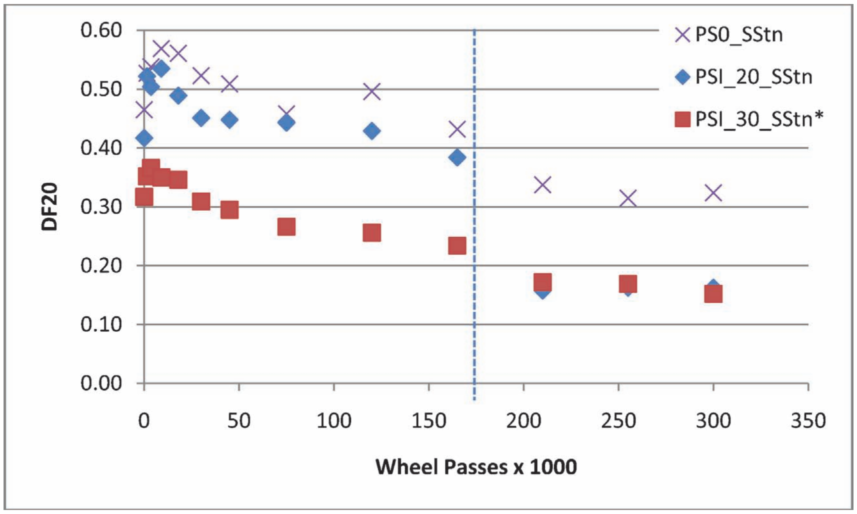

Figure D.10 DF_{20} results for DGA mixes with sandstone and varying amounts of polish susceptible coarse aggregate.

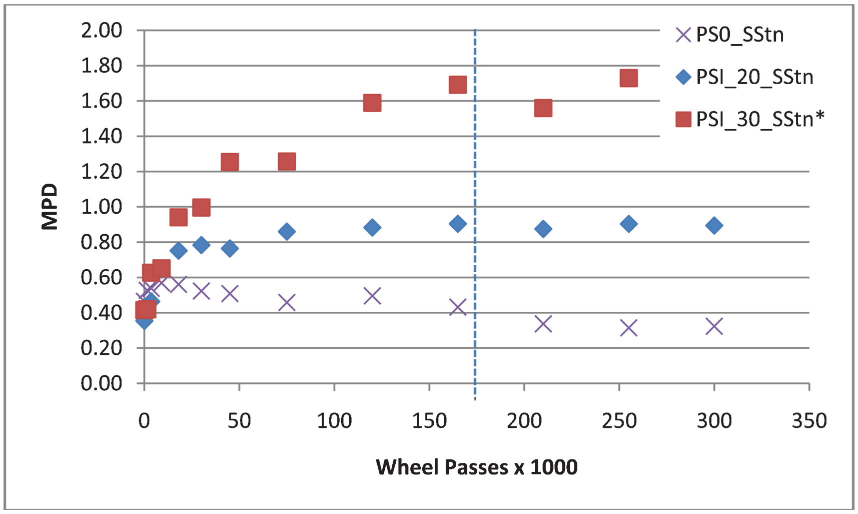

Figure D.11 MPD results for DGA mixes with sandstone and varying amounts of polish susceptible coarse aggregate.

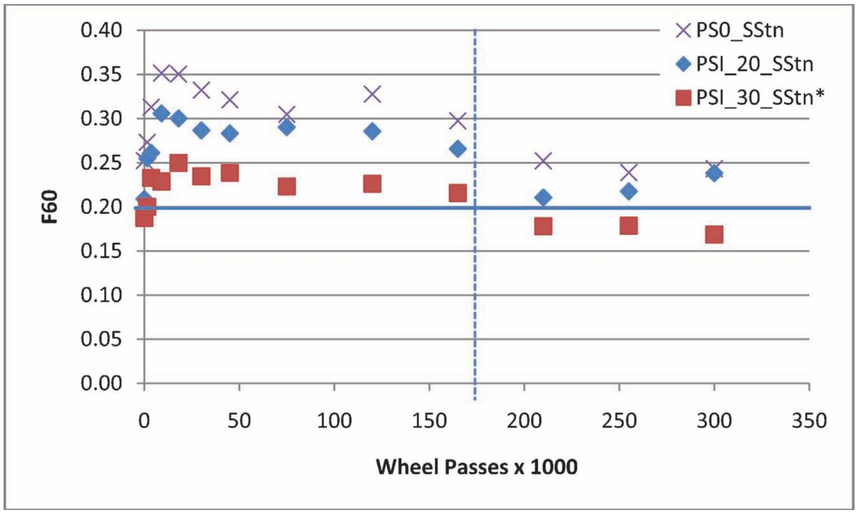

Figure D.12 F60 results for DGA mixes with sandstone and varying amounts of polish susceptible coarse aggregate.

F60 value would likely have been below the flag value. The other two mixes performed very well in terms of texture depth and were quite stable. This suggests that 30% PSI with sandstone is too high.

Figures D.13, D.14 and D.15 display the results of testing DGA mixes with 20% of PSI and PSII blended with steel slag coarse aggregate; the control mix with only steel slag coarse aggregate is shown for comparison. In this case, it appears that PSII is performing slightly better than PSI when blended at 20% with steel slag. And, both mixes with local aggregate are slightly below the control and well above the friction flag value at 165,000 wheel passes and beyond. The texture of the mix with PSII is somewhat higher than the other two mixes, but is not excessively high. In previous research, it was observed that mixes with steel slag tended to be less sensitive to the addition of lower frictional quality aggregates than mixes with quartzite, so it is not surprising perhaps that the addition of 20% local aggregate has relatively little effect on the mix friction, when used with steel slag coarse aggregate.

COARSE AGGREGATE STUDY—SMA MIXES

This section presents the results of testing the SMA mixes. The first three graphs, Figures D.16 through D.18, show the results of testing the SMA control mixes with no polish susceptible coarse aggregate. There is relatively little difference between the mixes through 165,000 wheel passes except that the sandstone mix has somewhat higher DF_{20} values in the early stages of polishing, as shown in Figure D.16. The MPD values are higher for the SMA mixes (around 1.2 mm) in general than for the DGA mixes (typically 0.8 mm to 1.0 mm), as expected. The F60 values in Figure D.18 are comparable at 165,000 passes and somewhat lower after additional passes were applied (after recalibration) but were still above the friction flag value.

The next three graphs show the comparison of the control mix with ACBF and a companion mix with 20% PSII and ACBF. As illustrated in Figure D.19, the mix with 20% PSII seems to have slightly higher friction in the early stages of polishing than the control but after about 18,000 wheel passes, the control's DF_{20}

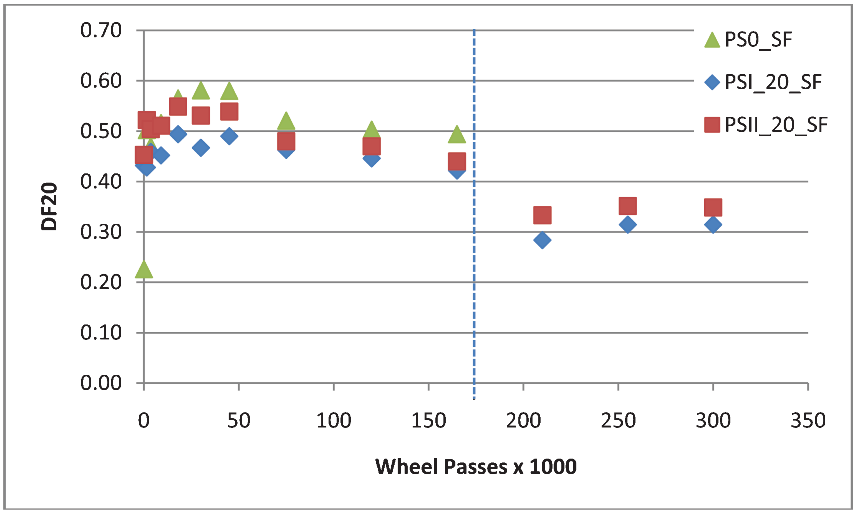

Figure D.13 DF_{20} results for DGA mixes with 0% and 20% PSI and PSII.

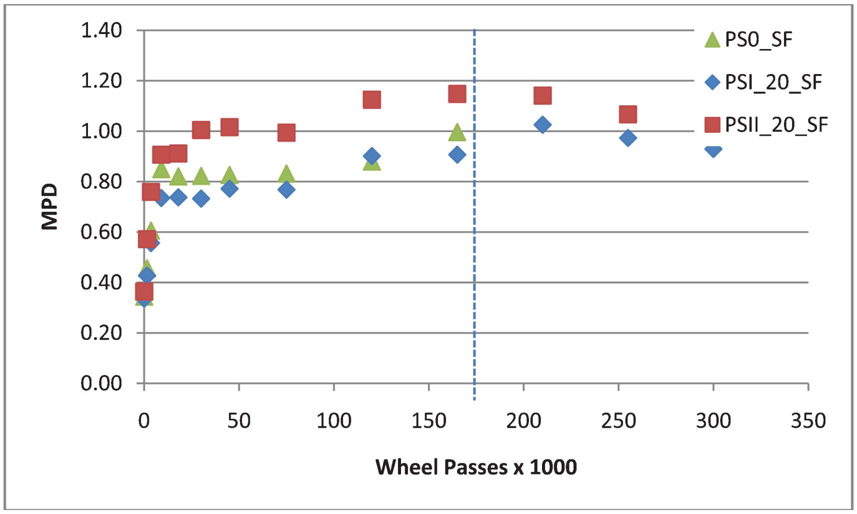

Figure D.14 MPD results for DGA mixes with 0% and 20% PSI and PSII.

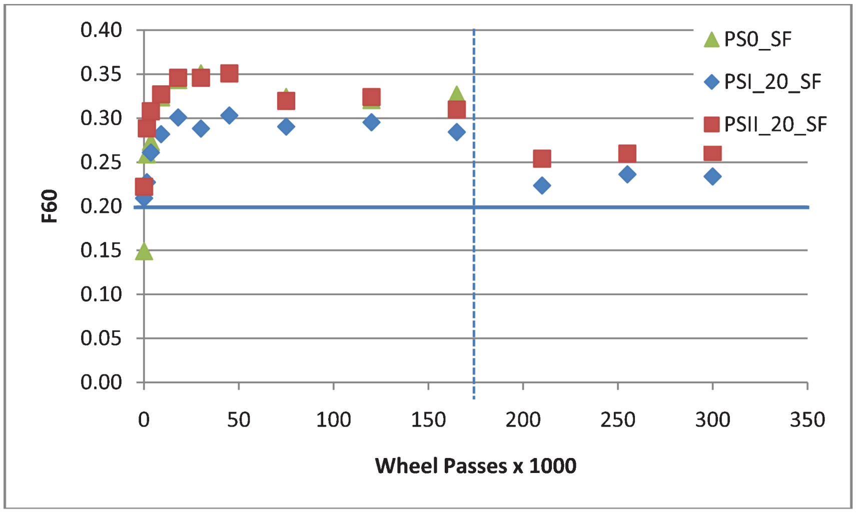

Figure D.15 F60 results for DGA mixes with 0% and 20% PSI and PSII.

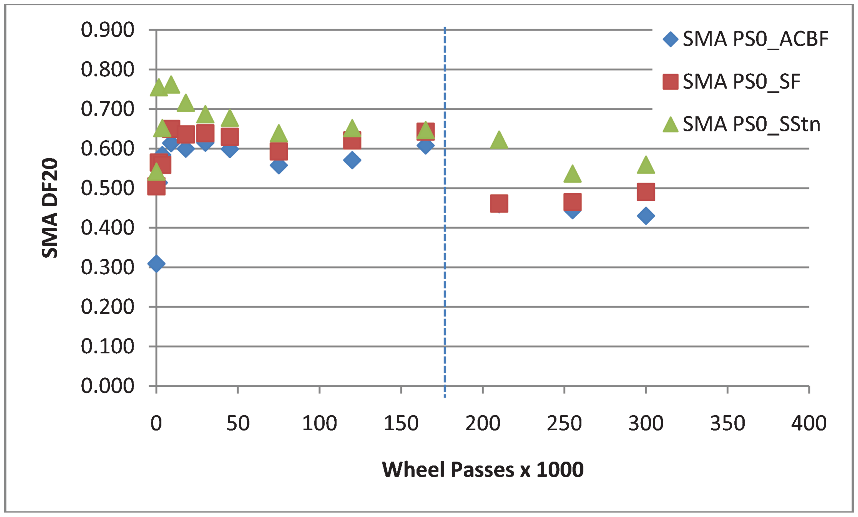

Figure D.16 DF$_{20}$ results for SMA mixes with 0% local aggregate.

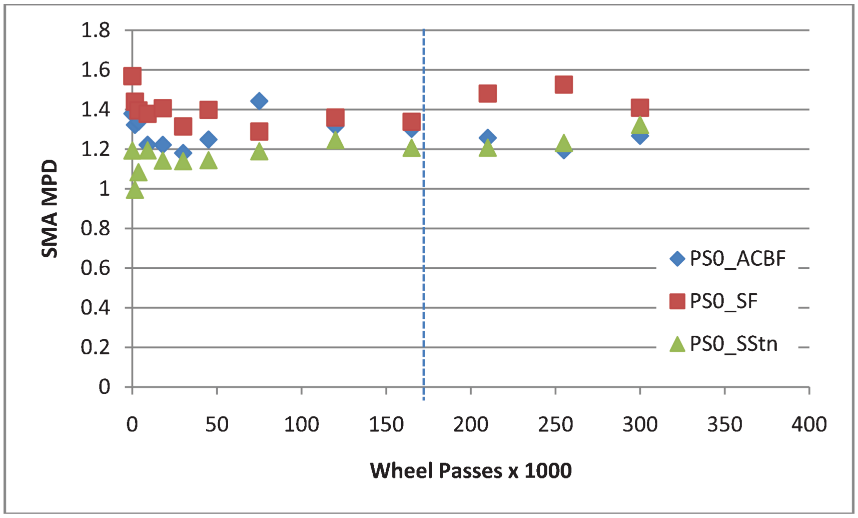

Figure D.17 MPD results for SMA mixes with 0% local aggregate.

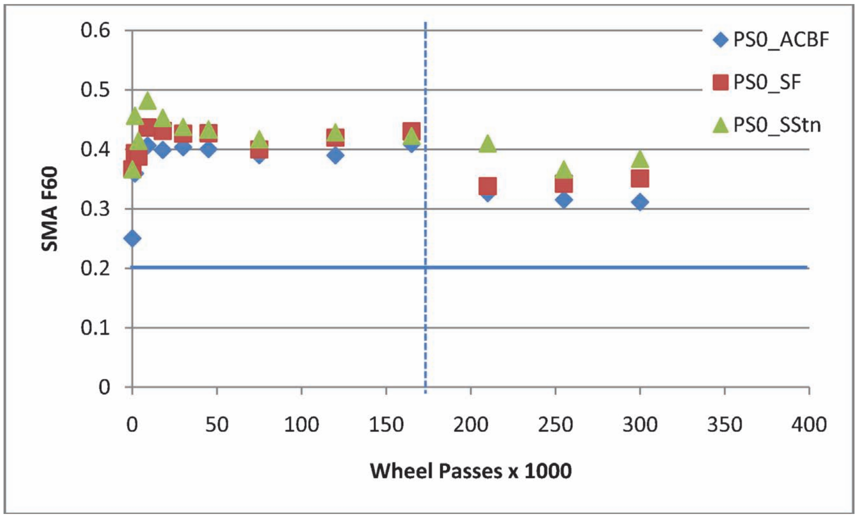

Figure D.18 F60 results for SMA mixes with 0% local aggregate.

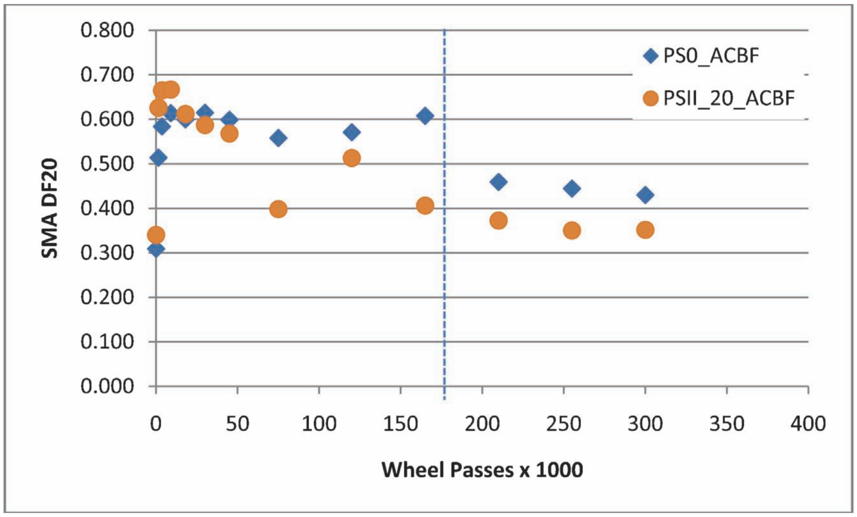

Figure D.19 DF$_{20}$ results for SMA mixes with ACBF and 0% or 20% local aggregate.

values exceed those of the mix with PSII. This is also reflected in the F60 values in Figure D.20, which all easily exceed the friction flag value. Figure D.21 shows that the macrotexture of the two slabs is quite comparable.

A comparison of SMA mixes with 0, 10, 20 and 40% of PSII blended with steel slag is shown in Figures D.22 through D.24. The DF$_{20}$ values, shown in Figure D.22, do not vary as much as in most previous examples. The MPD values in Figure D.23 are also quite consistent, except that the slab with 40% PSII exhibits some slightly lower values. (Some variations in MPD are likely due to slight misalignment of the CTM on the slab.) Figure D.24 shows relatively small deviations in the F60 values. The control with 0% PSII has the highest value and the 40% PSII slab has the lowest value, but the differences are quite small.

A comparison of PSI and PSII when blended with steel slag is shown in Figures D.25 through D.27; the control with steel slag but no local coarse aggregate is also shown. As in previous examples, the control mix exhibits the highest friction values, in terms of DF$_{20}$ in Figure D.25 and also F60 in Figure D.27. There is little difference between the performance of the PSI and PSII aggregates at 20%. All of the F60 values easily exceed the target value. The macrotextures of the slabs changed little during polishing, as typical for the SMA mixes evaluated in this and other studies.

The next set of three graphs shows the control mix with sandstone versus the mix with sandstone blended with 20% PSII. Both Figures D.28 and D.29 show that the friction values are fairly stable and the control mix has higher friction values than the mix with 20% PSII, but both are significantly higher than the friction flag value. The MPD values shown in Figure D.30 are also fairly stable.

SR62 STUDY

The results of the laboratory comparison of the mixes from SR62 are illustrated in Figures D.31, D.32 and D.33. Unfortunately, the fact that the slabs with PRA, but according to the field and lab gradations were performed after the DFT was recalibrated and the slag and slag_PRA blends were tested, to 165,000 wheel passes, before the recalibration, which makes the comparison of the PRA to the other mixes perhaps less reliable than desired. Given that caveat, however, the comparison does show that the slag and slag_PRA mixes have similar frictional characteristics, as shown in Figures D.31 and D.33.

Figure D.32, however, shows that the texture depths of these specimens varies greatly. The mean texture depths of the

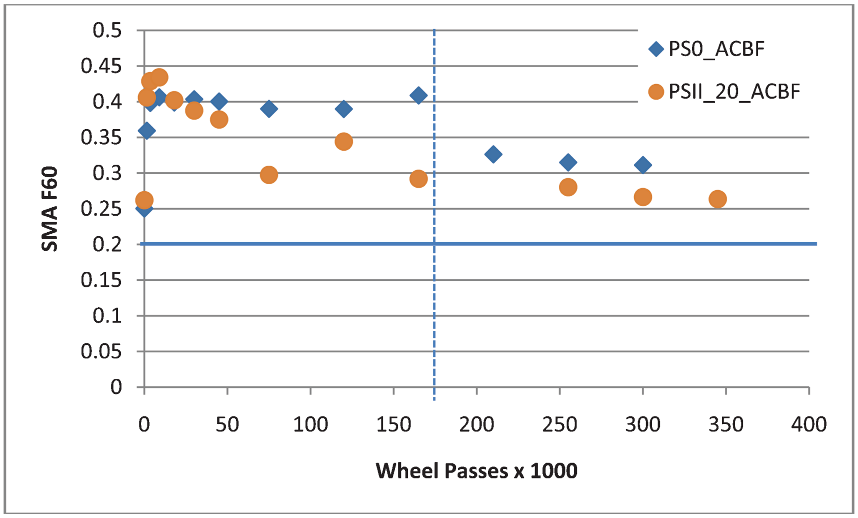

Figure D.20 F60 results for SMA mixes with ACBF and 0% or 20% local aggregate.

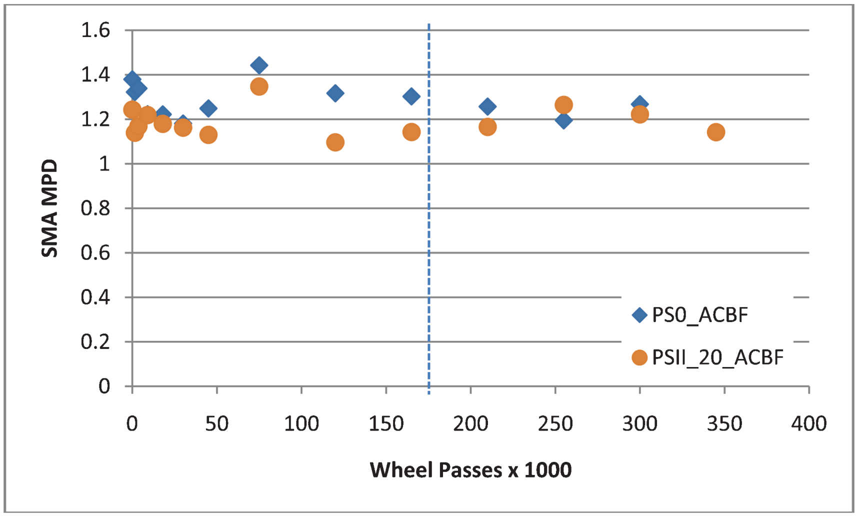

Figure D.21 MPD results for SMA mixes with ACBF and 0% or 20% local aggregate.

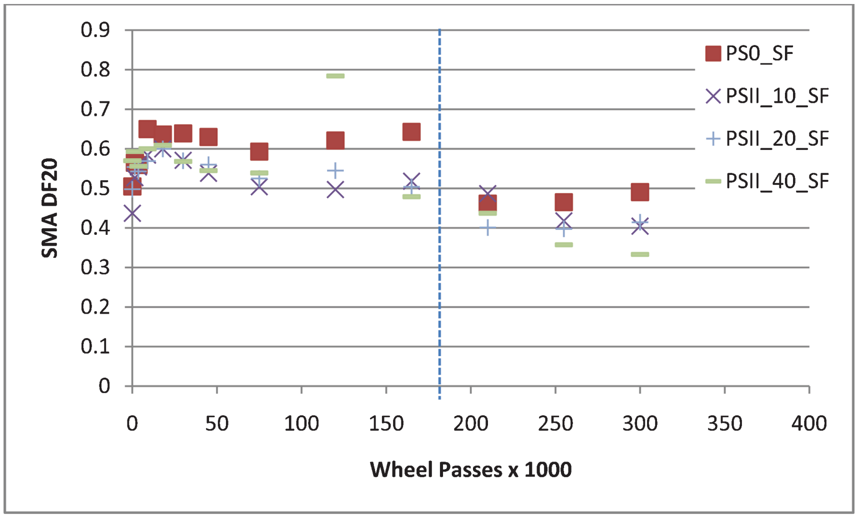

Figure D.22 DF_{20} results for SMA mixes with steel slag and varying amounts of PSII.

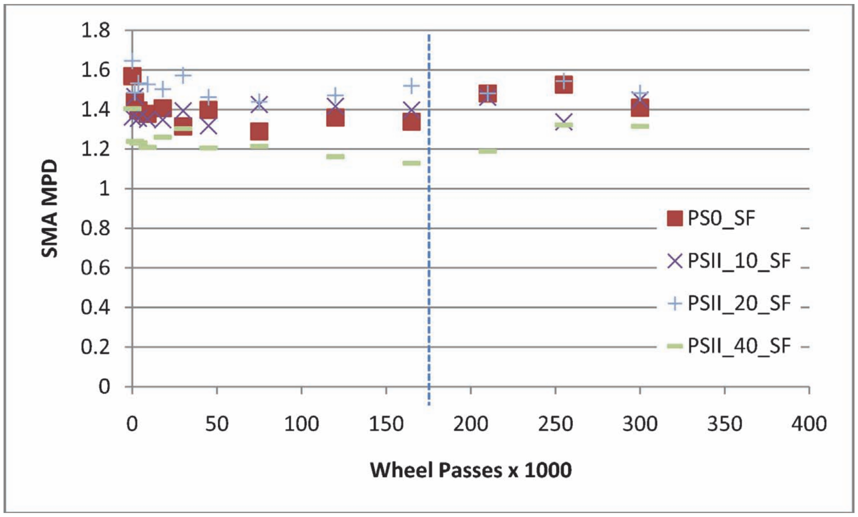

Figure D.23 MPD results for SMA mixes with steel slag and varying amounts of PSII.

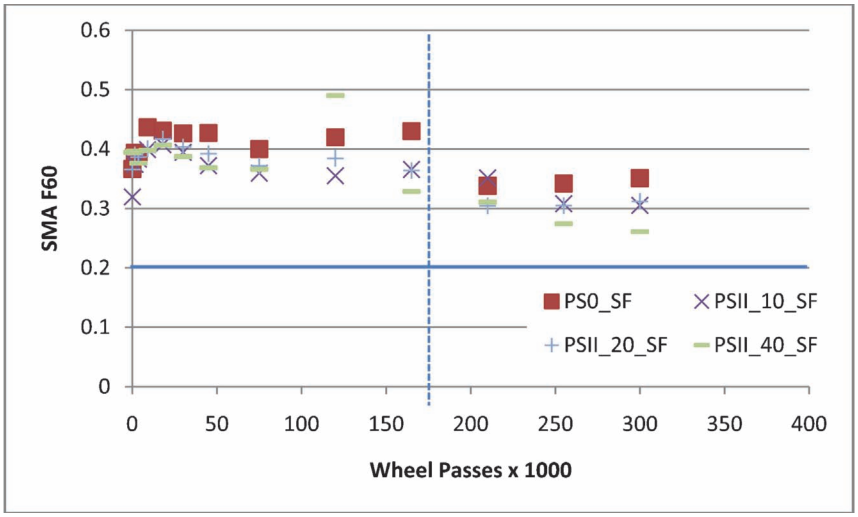

Figure D.24 F60 results for SMA mixes with steel slag and varying amounts of PSII.

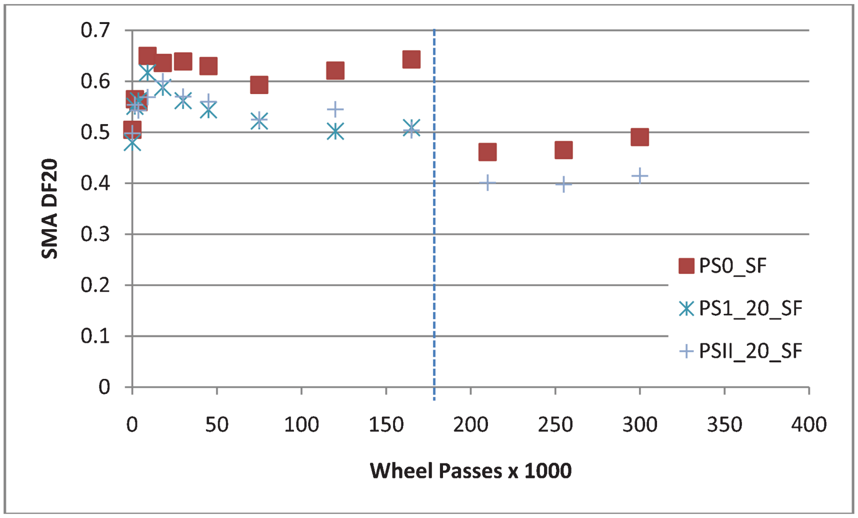

Figure D.25 DF_{20} results for SMA mixes with 0% and 20% PSI and PSII and steel slag.

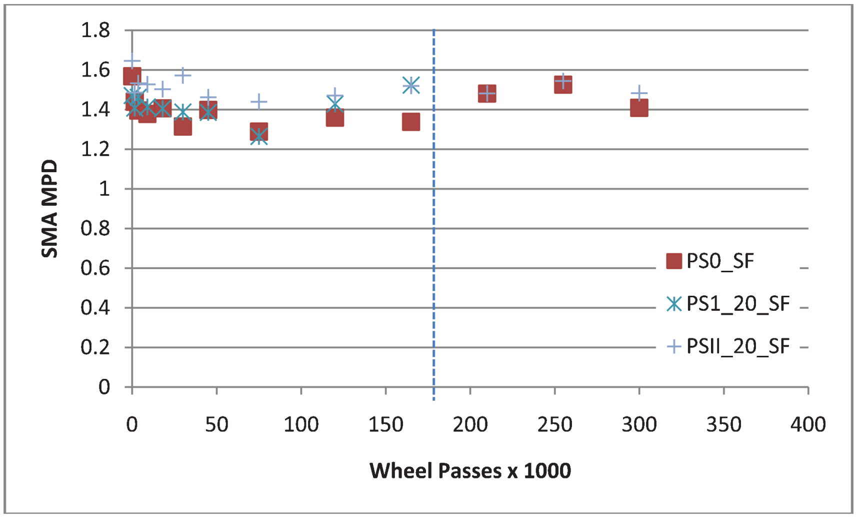

Figure D.26 MPD results for SMA mixes with 0% and 20% PSI and PSII and steel slag.

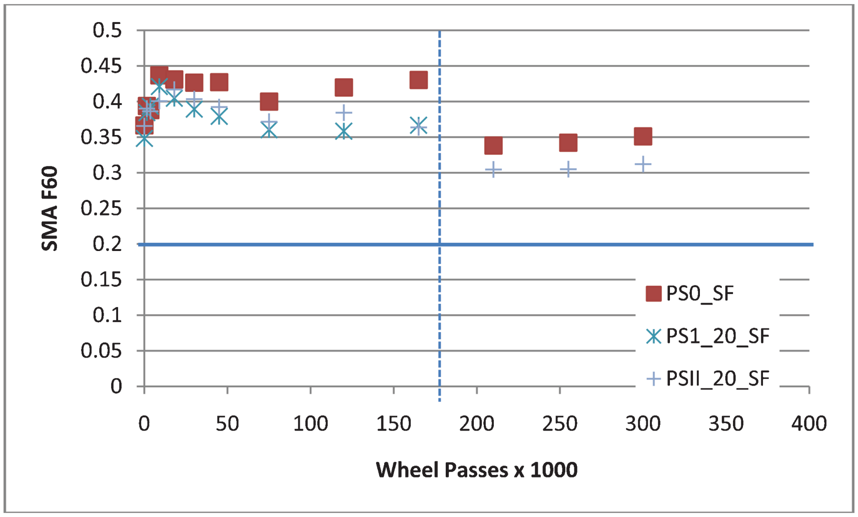

Figure D.27 F60 results for SMA mixes with 0% and 20% PSI and PSII and steel slag.

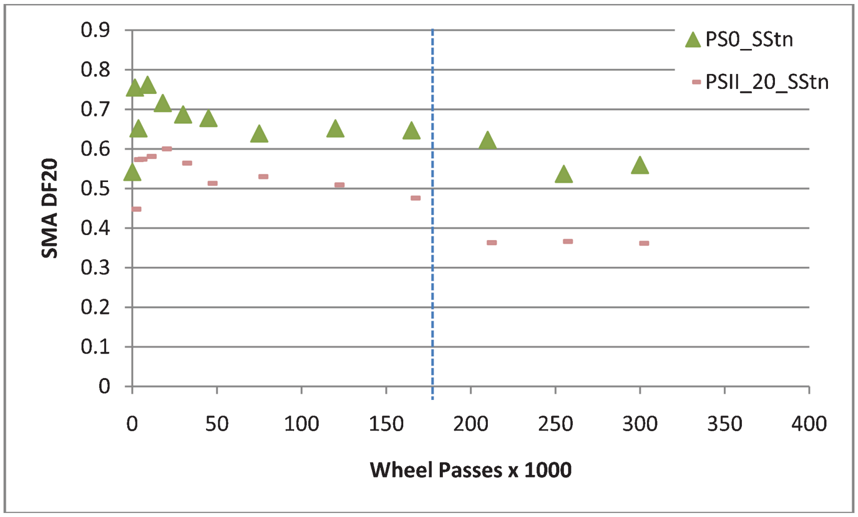

Figure D.28 DF_{20} results for SMA mixes with 0% and 20% PSII with sandstone.

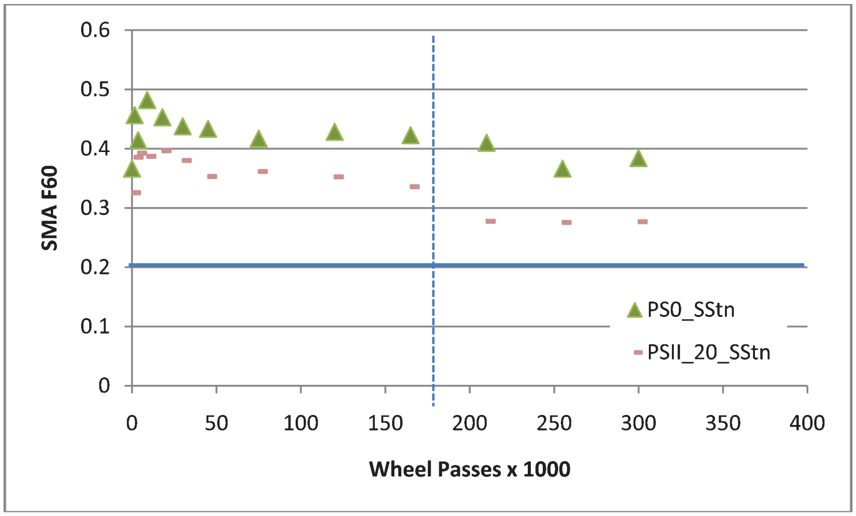

Figure D.29 F60 results for SMA mixes with 0% and 20% PSII with sandstone.

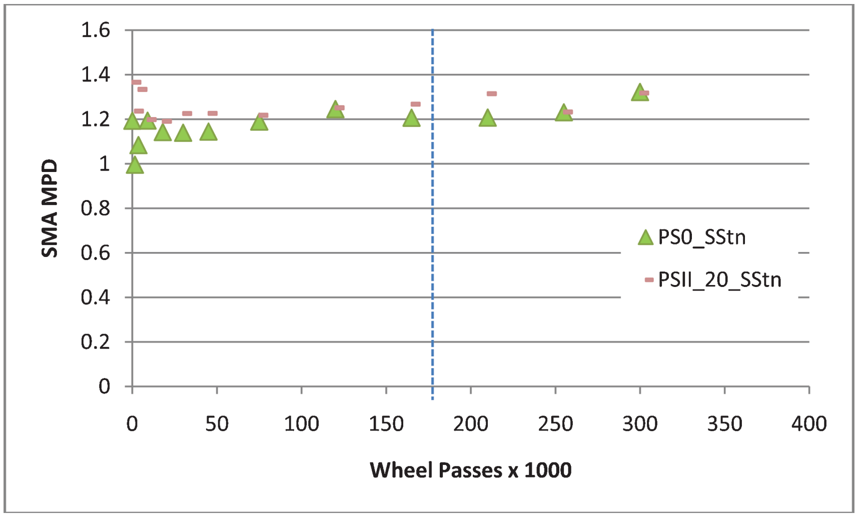

Figure D.30 MPD results for SMA mixes with 0% and 20% PSII with sandstone.

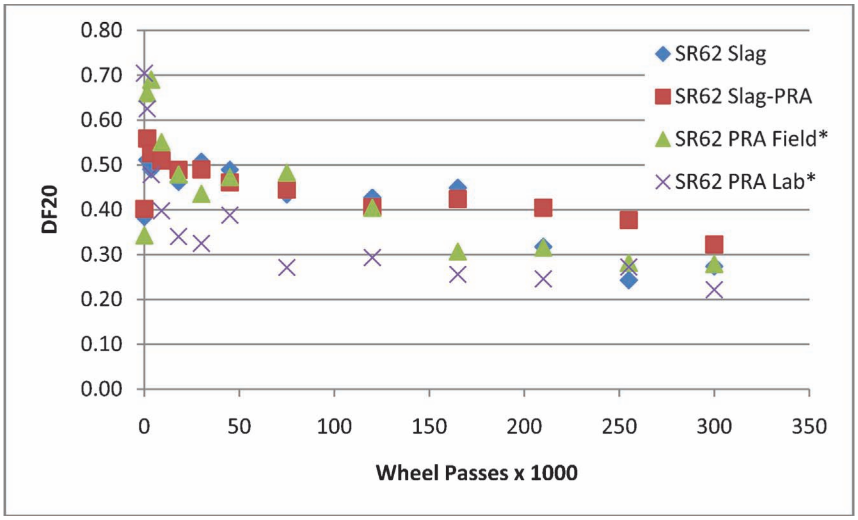

Figure D.31 DF_{20} results for SR62 study mixtures.

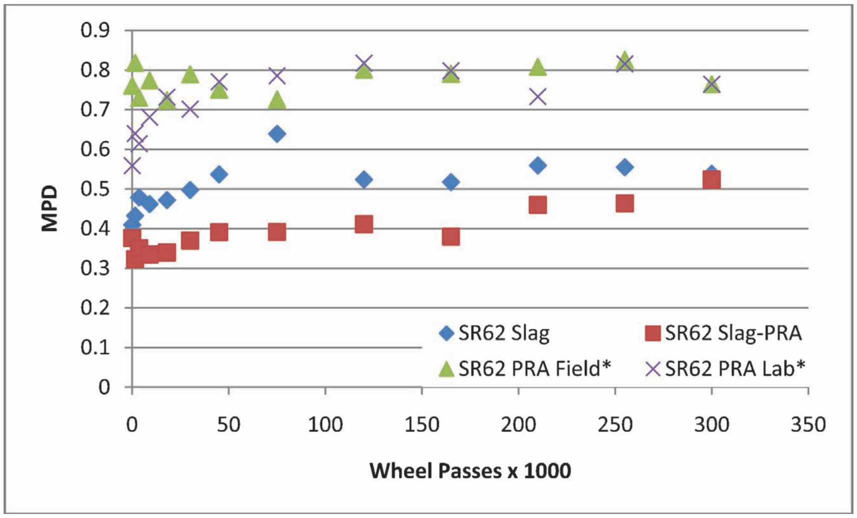

Figure D.32 MPD results for SR62 study mixtures.

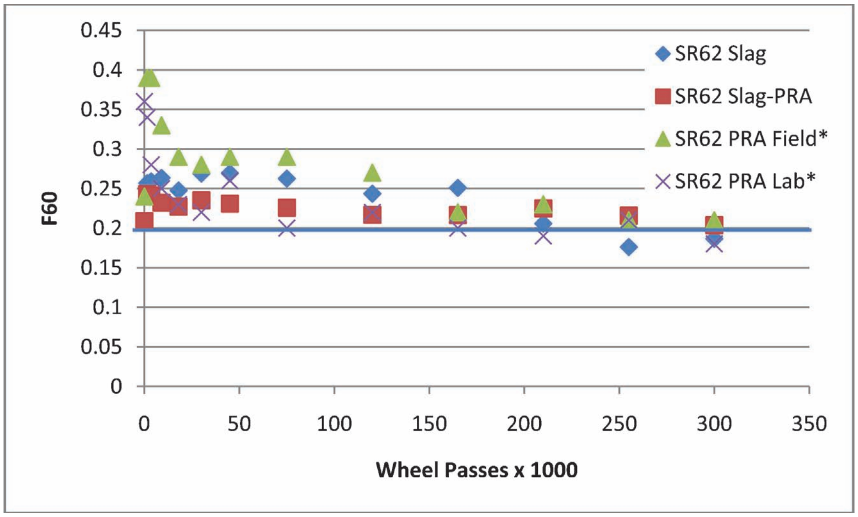

Figure D.33 F60 results for SR62 study mixtures.

slag_PRA blend are the lowest and those of the PRA only mixes, lab and field, are almost twice as high. The slag only blend had macrotexture somewhat higher than the slag-PRA. Although the DF_{20} value has the greatest influence on the F60 value, the texture does affect the F60 calculations, so if the macrotextures of the slag and slag_PRA values had been more representative of other DGA mixtures, the F60 values for those mixes would have been higher. The unusually low texture depths of these mixes may have been because these were field fabricated mixes that had been stored for some time before the slabs were compacted. The PRA_Field mix was also field-produced and stored, so it is unknown why this mix could be compacted to texture depths that were similar to other DGA mixes.

The data shows that the F60 values of all four mixtures appear to be approaching the flag value at 165,000 wheel passes, but the low macrotexture of the PRA only mixes may be causing those F60 values to be slightly lower than they would be if the macrotextures had been comparable to the other slabs. So, it is likely the F60 values would all have been at least somewhat over the flag value, with the slag only blend slightly higher than the other mixes. (The field friction test results have been requested to compare the actual friction values to the lab-measured values.)

FINE AGGREGATE STUDY

Lastly the results of the Fine Aggregate study are presented. In general, the Fine Aggregate mixtures exhibited much greater increases in texture depth, that is, more raveling, than the DGA and SMA mixes. Almost all of the mixtures exhibited this behavior, however, so comparisons between them are still reasonable. All of these samples were tested after recalibration of the DFT device, so the values have been corrected.

The first three graphs show the control mixes with no local fine aggregate. The DF_{20} values shown in Figure D.34 generally remain fairly high. This may be in part because there is significant loss of material (and corresponding increase in texture depth) as shown in Figure D.35. These combine to produce fairly high F60 values, shown in Figure D.36. In this case, the ACBF yielded a somewhat lower F60 value than the steel slag, which in turn was slightly lower than the sandstone mix at 165,000 wheel passes, but all were well above the friction flag value.

In the next three graphs, Figures D.37, D.38 and D.39, the comparisons of the mixes with ACBF slag with 0%, 10% and 20% local fine aggregate are shown. The data here shows more variability than is typical, probably because of the changes in the

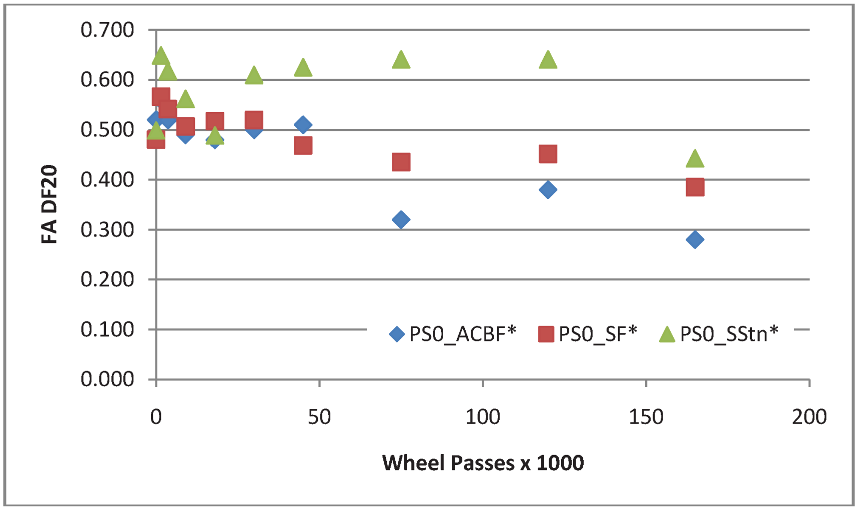

Figure D.34 DF_{20} results for DGA mixtures in fine aggregate study with 0% local aggregate.

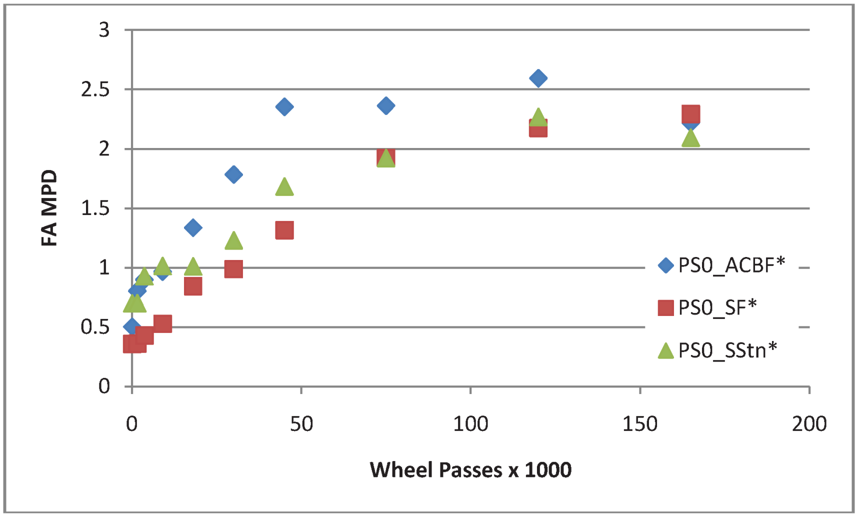

Figure D.35 MPD for DGA mixtures in fine aggregate study with 0% local aggregate.

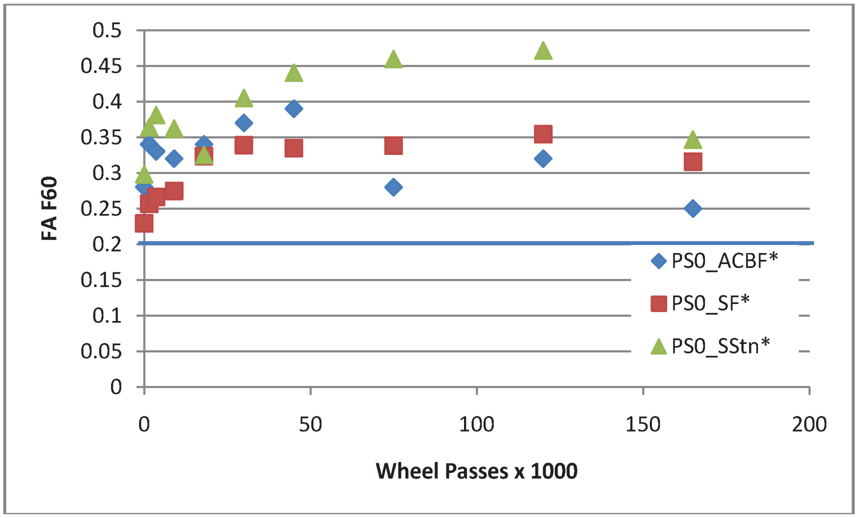

Figure D.36 F60 for DGA mixtures in fine aggregate study with 0% local aggregate.

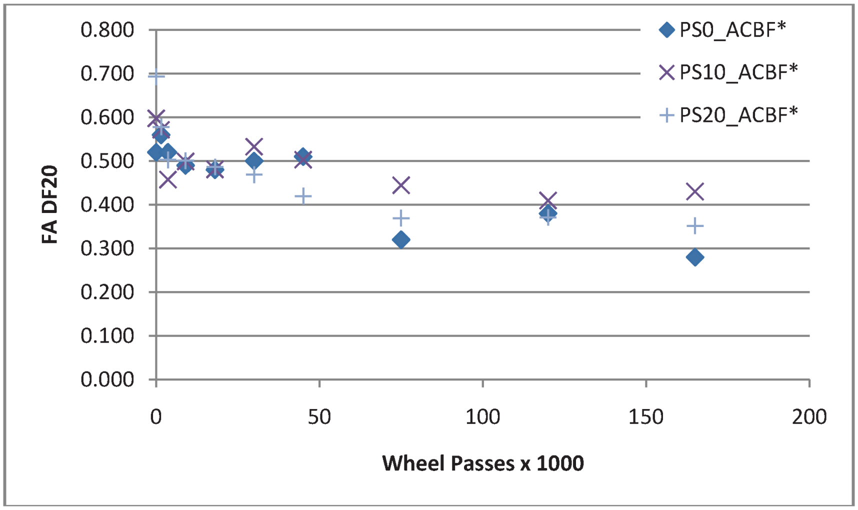

Figure D.37 DF_{20} results with ACBF and varying polish susceptible fine aggregate contents.

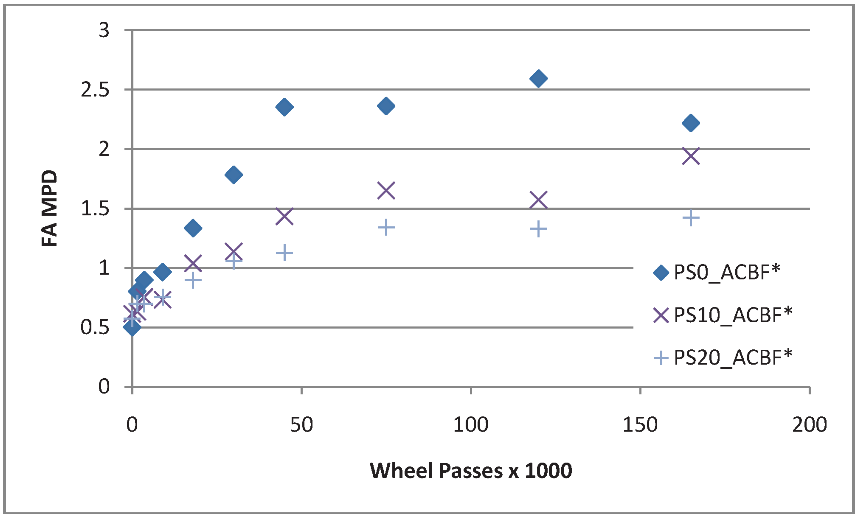

Figure D.38 MPD results with ACBF and varying polish susceptible fine aggregate contents.

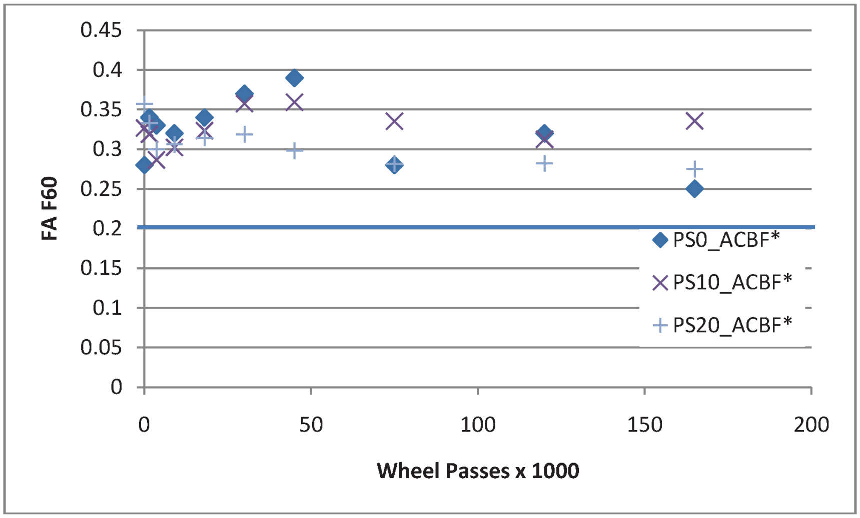

Figure D.39 F60 results with ACBF and varying polish susceptible fine aggregate contents.

macrotexture, illustrated in Figure D.38. The control mix experienced greater changes in the texture, which makes its F60 value somewhat erratic and makes analysis of the data questionable.

Figures D.40, D.41 and D.42 present the results of testing the mixes with steel slag and 0%, 10% and 20% local fine aggregate. Again, the control slab experienced greater changes in texture than the other two slabs, but it is not quite as bad as with the ACBF control. The DF_{20} and F60 values are quite stable, overall, and show little difference between the 0 and 10% local aggregate contents and only a small decrease in friction with 20% local fine aggregate. All of the F60 values are well above the friction flag value.

The results of testing the mixes with sandstone and varying amounts of local fine aggregate are shown in Figures D.43, D.44 and D.45. Ultimately these mixes exhibited about the same change in texture at 165,000 wheel passes. The DF_{20} values for the control tended to be higher than for the other two mixes until the 165,000 passes mark, at which time all three mixes had about the same friction level. The F60 results followed the same trend. It is unclear whether the control sample did experience more polishing between 120,000 and 165,000 wheel passes or whether this is an outlier—there are no obvious problems with the data. Again, however, all three mixes are provided friction levels in excess of the flag value.

OVERALL CONCLUSIONS AND OBSERVATIONS

The following conclusions may be drawn about the friction levels of the various mixes based on the preceding results and discussion.

COARSE AGGREGATE IN DGA

- The control mixes with steel furnace slag, air cooled blast furnace slag and sandstone with no local coarse aggregate provided similar friction levels, with the sandstone being only slightly lower than the two slags.
- Adding a polish susceptible local coarse aggregate to mixes with the three high quality friction aggregates did result in decreases in the friction levels.

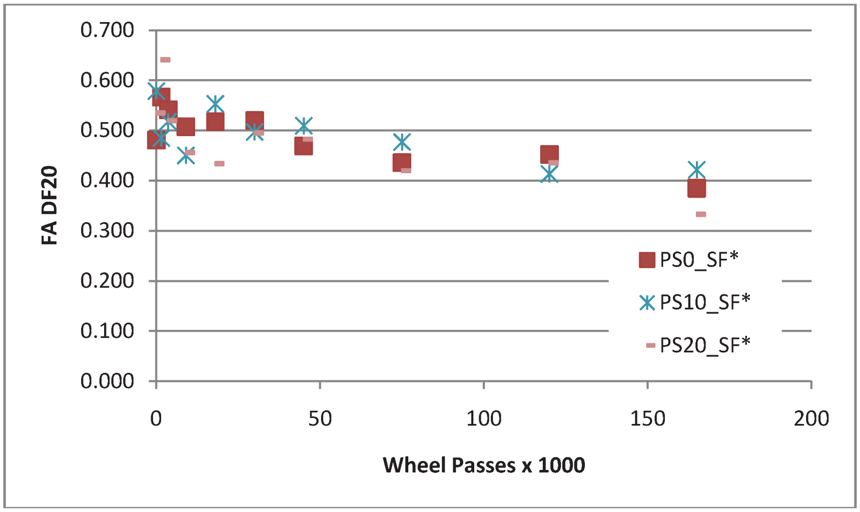

Figure D.40 DF$_{20}$ results for steel slag with varying polish susceptible fine aggregate contents.

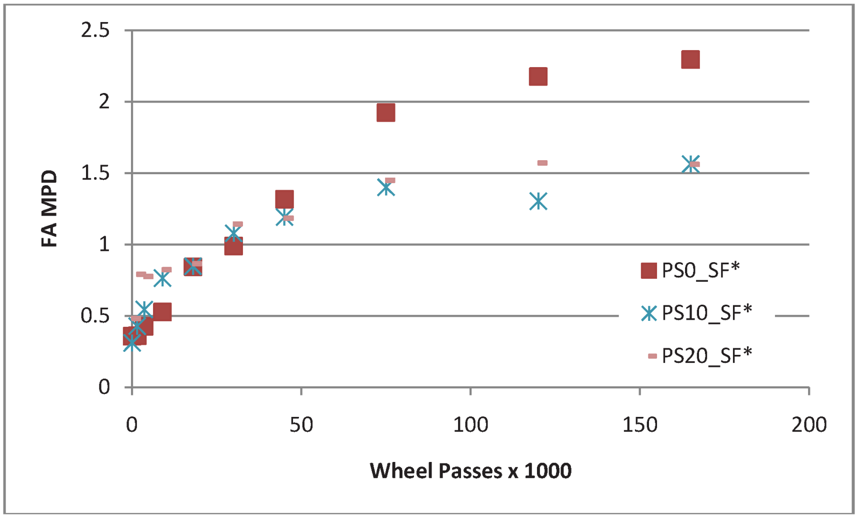

Figure D.41 MPD results for steel slag with varying polish susceptible fine aggregate contents.

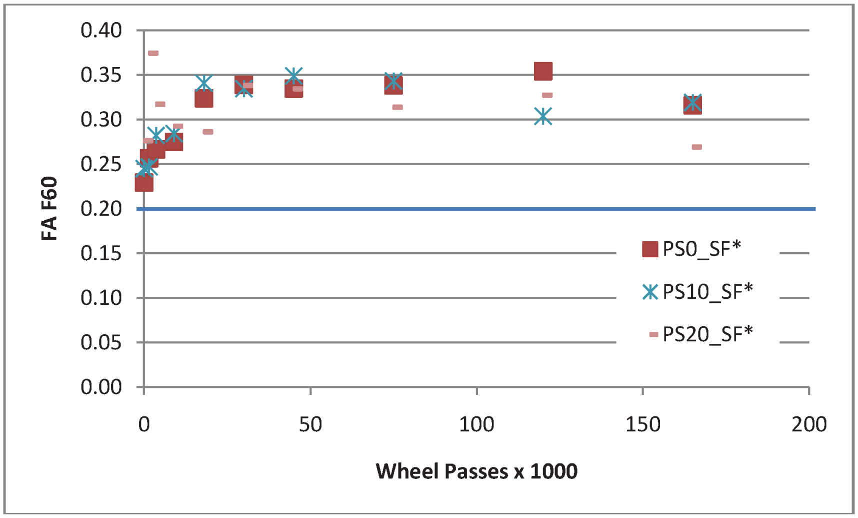

Figure D.42 F60 results for steel slag with varying polish susceptible fine aggregate contents.

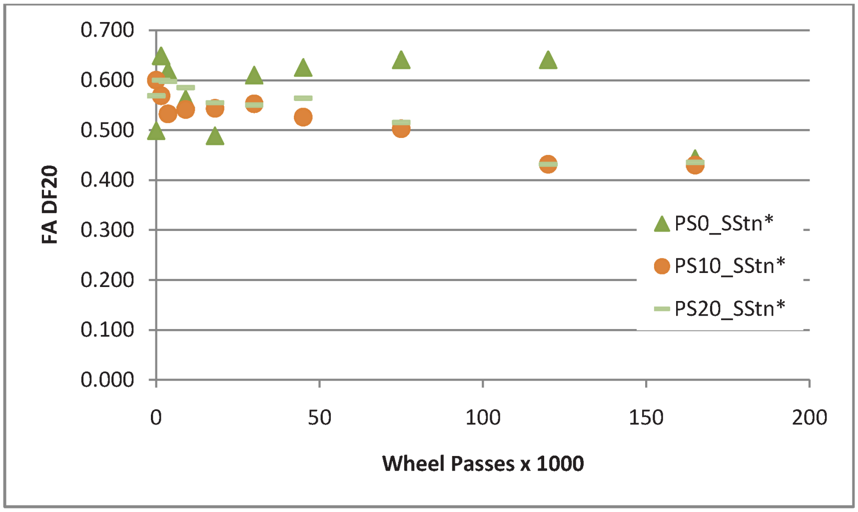

Figure D.43 DF_{20} results for sandstone and varying polish susceptible fine aggregate contents.

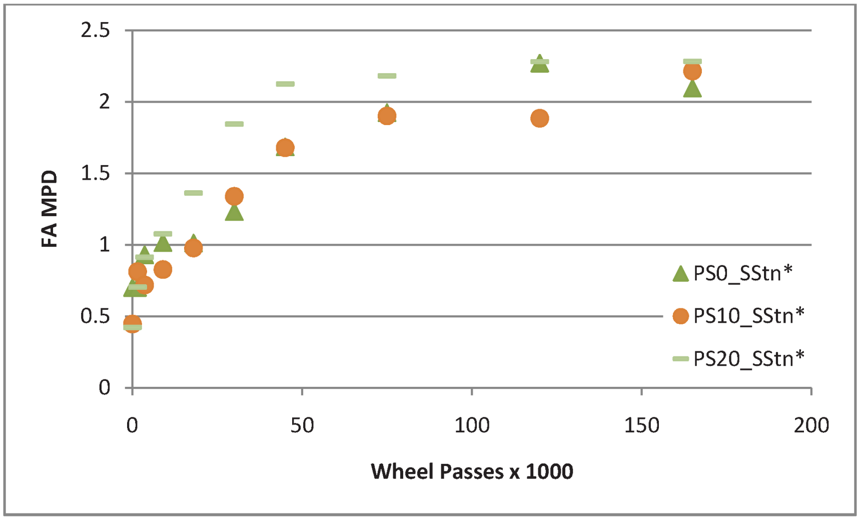

Figure D.44 MPD results for sandstone and varying polish susceptible fine aggregate contents.

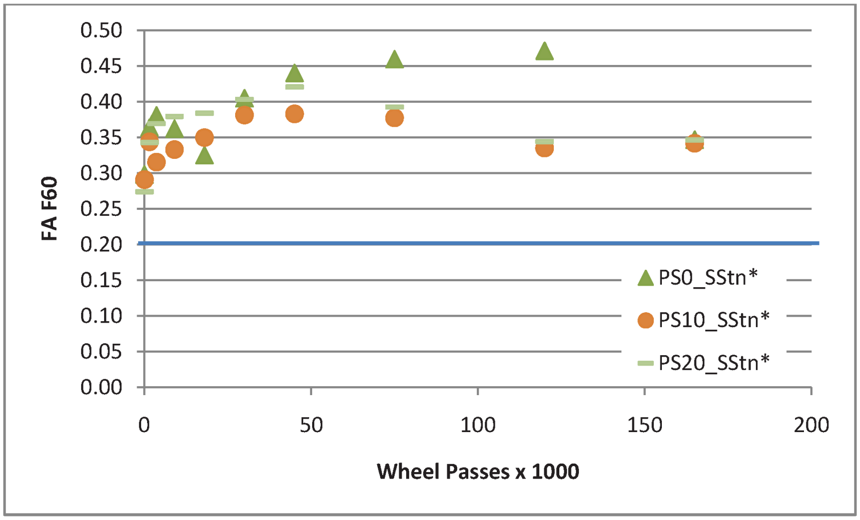

Figure D.45 F60 results for sandstone and varying polish susceptible fine aggregate contents.

- Adding 20% of a local coarse aggregate to the mix with ACBF decreased the friction somewhat but it was still in excess of the friction flag value. The mix with 30% local aggregate was marginal in terms of the flag value.
- With steel slag, adding a polish susceptible aggregate (PSI) lowered the friction level, but there was little difference with 10% and 20% PSI and those mixes provided friction above the friction flag value. The mix with 25% PSI may also be acceptable, but this mix also had the highest macrotexture, which may have increased the friction level. The addition of 30 and 40% PSI coarse aggregate appears to have caused too great a decrease in friction, especially considering that these mixes also had higher macrotexture than the mixes with lower amounts of PSI.
- Adding 20% local coarse aggregate to the mix with sandstone provided friction in excess of the flag value, but the mix with 30% was marginal.
- When added to steel slag coarse aggregate, there was little difference between adding 20% PSI or 20% PSII. The friction of the mix with 20% PSI was slightly lower than the mix with 20% PSII and the control mix was comparable.
- It appears adding 20% local coarse aggregate blended with one of the high quality friction aggregates would still provide adequate friction. This should be validated in the field before considering allowing higher amounts, such as 25%.

COARSE AGGREGATE IN SMA

- In general, the SMA mixes provided higher friction levels than the DGA and experienced less change in the surface texture.
- The three control mixes provided comparable friction levels.
- Adding 20% PSII to the mix with ACBF lowered the friction level, but it was still greater than the friction flag value.
- Adding increasing amounts of PSII to the mix with steel furnace slag resulting in greater decreases in the friction level. The performance was higher than the flag value up to 40% and there was little difference between 10% and 20% PSII.
- With steel slag, the mixes with 20% PSI and 20% PSII were comparable. Though both provided friction levels below that of the control, they were still well above the flag value.
- Adding 20% PSII to the sandstone mix also lowered the friction but it was still in excess of the flag value.
- Adding 20% local coarse aggregate blended with one of the high quality friction aggregates appears possible from a frictional standpoint, but with SMA mixes in particular, there are other considerations, such as particle strength.

SR62 MIXES

- Analysis of the results from testing the SR62 mixtures is complicated by the recalibration of the DFT device since the recalibration occurred when some slabs had been polished and tested and others had not. The slag only and slag_PRA mixes had been tested to 165,000 wheel passes before recalibration, but both PRA only mixes were only tested after recalibration.
- Significant variations in the texture depths also complicate the interpretation of the results. The PRA only mixes (both lab fabricated and field sampled) had much higher macrotextures than the other two mixes.
- This is the first time the NCSC has tested field produced mixes that have been stored for any period of time, and it is unknown if this could have affected either the compactability of the mixes or their eventual performance.
- The differences among the mixtures do not appear to be great, but at 165,000 wheel passes, the slag mix is performing the best and the slag_PRA and PRA only mixes are approaching the flag value.
- When additional wheel passes were applied, the slag_PRA and PRA only mixes provided slightly higher friction levels than the slag only mix.
- Based on these results, with the caveats above, the use of the PRA only aggregate does not appear to be problematic from a frictional point of view, at least for low to moderate traffic volumes.
- These results should be compared to field friction test results for further examination.

FINE AGGREGATE STUDY

- The mixes with varying amounts of local fine aggregate exhibited much greater changes in texture depth than the other mixes. In most cases, the texture depth stabilized after about 50,000 wheel passes. It is not known if this is because of poor compaction of the mixes or their greater sensitivity to the shearing action of the tires on the polishing machine. The change in the texture may have been causing new, unpolished aggregate surfaces to be exposed, which would affect the friction results. Since the texture generally did not change much after 50,000 passes, examining the terminal friction levels seems reasonable.
- The control mix with ACBF provided a lower friction level than the control with steel slag or sandstone.
- The results of testing mixes with ACBF and different amounts of local fine aggregate were erratic but the friction levels at 165,000 wheel passes appear to be acceptable.
- When local fine aggregate was blended with steel slag, there was little difference between the control and 10% local aggregate. The mix with 20% local fine aggregate also appeared to provide acceptable friction levels.
- The friction levels were above the flag value for the mixes with 0%, 10% and 20% local fine aggregate when blended with sandstone and the results were comparable at 165,000 wheel passes. The sandstone only control, however, provided higher friction levels than the mixes with local fine aggregate between 50,000 and 120,000 passes; it is unknown if the last data point for the control mix is accurate or an outlier.
- The overall results of the fine aggregate study are less conclusive than those of the coarse aggregate study. Nonetheless, it does appear that a small amount of local fine aggregate can be added to DGA and SMA mixtures without detrimental effect on the resulting friction levels. This seems reasonable since it is widely held that most of the frictional resistance of asphalt mixtures is provided by the coarse aggregate. Before the specifications are greatly changed, it would be prudent to do additional research in the lab or field or preferably both.

GENERAL OBSERVATIONS

- This study evaluated only one size of mix, 9.5 mm. Previous research *(1)* has shown that larger nominal aggregate size mixes may provide higher friction levels. There is also evidence that smaller nominal aggregate size mixes may require higher frictional quality aggregates, in part at least, because of their reduced macrotexture. Extension of these findings and recommendations to other mix sizes should be done cautiously and preferably should be guided by additional research in the lab and/or field.
- Another previous study evaluated the potential effects of poor quality aggregate in reclaimed asphalt pavement (RAP) if the RAP is reused in high volume surface mixes. The final report on that project *(2)* suggests that up to 20%–25% poor frictional quality RAP could be used in surface mixes without detrimental effect on the friction level. The possible

allowable local aggregate levels recommended in this study are in substantial agreement with that other study. This is reasonable since once in the mix, the aggregate behaves the same whether it came from RAP or was virgin aggregate, at least in terms of friction.

- The laboratory techniques used in this study are definitely useful since trial mixes or new materials can be evaluated without risk to the public. Additional refinement is recommended, however, to develop them more fully and address some of the problem noted in this study. Particularly, there is a need to examine the compaction process, equipment calibration and data interpretation. Further comparisons of the lab and field measured friction levels to further refine the friction flag value would also be extremely useful. The procedures could then be used as a screening test to approve new aggregates or mix types for field trials, similar to the approach in the current ITM 214 *(3)*.
- These results may be useful for opening up the specifications somewhat but a conservative approach is recommended until field testing verifies the accuracy of the lab results.

REFERENCES

1. Kowalski, K., R. S. McDaniel, and J. Olek. Development of a Laboratory Procedure to Evaluate the Influence of Aggregate Type and Mixture Proportions on the Frictional Characteristics of Flexible Pavements. *Journal of the Association of Asphalt Paving Technologists*. Vol. 77, 2008, pp. 35–70.
2. Kowalski, K. J., R. S. McDaniel, and J. Olek. *Identification of Laboratory Technique to Optimize Superpave HMA Surface Friction Characteristics*. Publication FHWA/IN/JTRP-2010/06, Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2010. doi: 10.5703/1288284314265.
3. ITM 214. *Acceptance Procedures for Polish Resistant Aggregates.* Indiana Department of Transportation, Indianapolis.

APPENDIX E
SR62 FIELD FRICTION TESTING RESULTS

The INDOT Office of Research and Development has performed special friction testing on the SR62 field test section. That testing has resulted in the friction values in Table E.1 to date.

These results suggest that the PRA only mix had a significantly higher friction value initially, being 10 points or more higher than the other two mixes. The reason for this is unknown. The mixes were only a few months old at the time of first testing, which may have impacted the results. By the time of the second test, in May 2011 when the mixes were approaching one year old, the friction values were much more similar but the PRA only was still slightly higher than the steel slag only and slag/PRA blend. In October 2011, the values were all very similar, falling within a range of less than 2 points. The PRA only blend is now intermediate between the other two mixtures, but there is essentially no significant difference in the values. All the mixtures are demonstrating good performance to date and are well above the INDOT friction flag value.

TABLE E.1
Field Friction Testing Results on SR62[*]

	Test Date		
Section	**11/17/2010**	**5/24/2011**	**10/4/2011**
Steel slag	30.7	27.9	37.7
PRA	40.5	30.7	36.5
Slag/PRA	26.0	25.8	35.9

[*] Smooth tire tests(FN40).

The mixtures followed a similar trend in the laboratory. The initial friction readings on the PRA only mix (field produced) were initially higher than the other two mixes. Then after 165,000 wheel passes the slag mix yielded somewhat higher values. After 200,000 wheel passes, all three mixes had similar F60 values. The field friction testing should be continued to monitor how the friction values change over time with actual traffic.