NCAT Report 15-04

HIGH FRICTION SURFACE TREATMENT ALTERNATIVE AGGREGATES STUDY

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16. Abstract
The objective of this study was to examine the pavement surface friction performance of seven alternative aggregate sources in the United States to determine if they provided similar performance to calcined bauxite as a high friction surface treatment (HFST). The alternative aggregates were granite, flint, basalt, silica sand, steel slag, emery, and taconite. The first laboratory study evaluated test slabs under accelerated laboratory polishing using the NCAT Three Wheel Polishing Device, dynamic friction tester, and circular texture meter. The field study evaluated HFST pavement test sections with the same eight aggregates under heavy truck loading at the NCAT Pavement Test Track. The second laboratory study evaluated four aggregates for the influence of particle size on HFST friction performance, and examined the British Wheel and Pendulum, AIMS, and Micro-Deval as simpler tests to qualifying friction aggregates in HFST specifications. Terminal surface characteristics were achieved after early conditioning (less than one month for field friction) both in the laboratory and in the field. The terminal texture and friction characteristics decreased very slowly during additional conditioning. All eight surfaces maintained good macro-texture, predominately greater than 1.0 mm MPD. The eight surfaces measured terminal DFT(40) friction values in the range of 0.84 to 0.49 in the lab and 0.79 to 0.43 in the field. There may be a correlation between HFST surface friction and Micro-Deval mass loss. There was no correlation between HFST surface friction and AIMS particle shape and angularity. An additional laboratory procedure is needed to prepare test specimens of small aggregate particles for the British Wheel and Pendulum friction test. There is no correlation between surface macro-texture and friction. Friction measured on HFST using alternative aggregates was not equal to HFST using calcined bauxite.

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LIST OF ABBREVIATIONS

AIMS .... Aggregate Image Measurement System
ASTM .... American Society for Testing and Materials
BP .... British Pendulum
COV .... coefficient of variation statistic
CTM .... Circular Texture Meter
DFT .... Dynamic Friction Tester
DFT(40) .... Dynamic Friction measured at 40 km/h
DOT .... Department of Transportation
ESALs .... Equivalent Single Axle Loads
FHWA .... Federal Highway Administration
FIELD .... Field study
Fn .... Friction number
ft .... foot
gr .... grams
HFST .... High Friction Surface Treatment
K .... thousand
km/h .... kilometers per hour
LAB-1 .... First lab study
LAB-2 .... Second lab study
lb .... pound, mass
M .... million
mm .... millimeter
MPD .... Mean Profile Depth
NCAT .... National Center for Asphalt Technology
psi .... pounds per square inch
QC .... quality control
R^2 .... coefficient of determination statistic
SN40R .... Skid Number at 40 mph with Ribbed Tire
TWPD .... Three Wheel Polishing Device

EXECUTIVE SUMMARY

High Friction Surface Treatments (HFST) are used to improve roadway surface conditions in locations with high crash rates. The more widely applied HFST specification recommends crushed calcined bauxite aggregate, which is an imported product. This series of studies examined the performance of seven alternative aggregate sources in the United States to determine if they provided similar friction performance. The alternative aggregates were granite, flint, basalt, silica sand, steel slag, emery, and taconite. The research was divided into three studies: LAB-1, FIELD, and LAB-2. The scope of LAB-1 evaluated HFST test slabs with the bauxite and seven alternative aggregates under accelerated laboratory polishing and testing procedures. The scope of FIELD evaluated friction performance of HFST pavement test sections with the same eight aggregates under heavy truck loading in the west end super-elevated curve at the National Center for Asphalt Technology (NCAT) Pavement Test Track. LAB-2 evaluated the influence of particle size on HFST friction performance and examined other laboratory aggregate tests as a simpler approach to qualifying friction aggregates in HFST specifications.

LAB-1 combined the surface polishing action of the NCAT Three Wheel Polishing Device (TWPD) with the friction measurement of the Dynamic Friction Tester (DFT) and surface macro-texture measurement of the Circular Texture Meter (CTM). Two test slabs for each of the eight aggregates were conditioned and tested using identical laboratory procedures. A random conditioning and testing protocol was applied and the quality of the test measurements was evaluated and found acceptable. DFT friction and CTM texture measurements were taken before conditioning and after 70,000 and 140,000 cycles of TWPD conditioning to evaluate long-term pavement surface friction performance of each aggregate.

LAB-1 showed that none of the seven alternative HFST aggregates provided friction comparable to bauxite based on the DFT measurements. Bauxite maintained a terminal friction value (DFT(40)) above 0.80, four aggregates (taconite, basalt, emery and flint) maintained values above 0.60, and two aggregates (silica sand and slag) measured terminal values at or below 0.50. All of the surfaces, except slag, maintained surface macro-texture mean profile depth (MPD) values at or above 1.4 mm. Even though bauxite measured the highest DFT friction values, the bauxite surface texture was lower than most of the aggregates. All of the test surfaces had surface texture values much higher than MPD in the range of 0.30 to 0.50 mm for conventional dense graded asphalt mixtures. The data showed no correlation between the terminal friction and terminal surface texture.

FIELD used a HFST contractor to install a full lane-width test section for each of the eight aggregates. Granite, bauxite, and flint were placed as 85 to 100 ft long sections and basalt, silica sand, steel slag, emery, and taconite were placed 15 ft long. All eight sections were conditioned by truck traffic for six months, an equivalent of 350,000 18-wheel tractor-trailer units. An additional 1,000,000 tractor-trailer units were applied to the three longer sections over an additional 18 months. The same DFT and CTM devices were used to measure friction and texture of field sections. Friction was also measured with the full-scale locked-wheel skid

trailer on the three longer sections. The planned test frequency was monthly or quarterly, but actual testing varied with equipment and staff availability and weather conditions. Replicate measurements were made with all test devices and data quality was evaluated for outliers.

The first step of the FIELD analysis examined the changes in HFST friction and texture to establish terminal values. All of the sections, except for basalt, showed a 0.20 to 0.30 mm drop in MPD texture values after approximately one month of traffic and in most cases texture continued to gradually decrease an additional 0.10 to 0.20 mm MPD through six months of traffic conditioning. The terminal texture values ranged from 1.10 to 1.50 mm MPD for all sections, except steel slag dropped below 0.90 mm. After one month of traffic, the wheel path DFT friction values for all of the HFST test sections had a general surface friction reduction of 0.15. The most probable explanation for the friction reduction within the first month is the traffic abrasion wearing down the sharp edges of the crushed faces of the aggregate particles. Most of the HFST test sections maintained their relative ranking of surface friction throughout the six-month conditioning period. Bauxite and taconite had the highest DFT(40) Fn terminal values (0.78 and 0.60 respectively) and slag and granite had the lowest terminal values (0.48 and 0.42 respectively) over this period. The three sections conditioned for an additional 18 months showed no change in the ranking of friction performance. Locked-wheel skid trailer data for the three longer sections was only reliable for the extended 18 months. The trend lines generated by the skid trailer SN40R data sets showed bauxite friction dropped from 70 to 63, flint dropped from 54 to 43, and granite dropped from 54 to 40. The results clearly show the bauxite HFST test section maintained higher friction levels over the 24 months of accelerated NCAT Pavement Test Track truck traffic conditioning.

LAB-2 had two objectives: (1) evaluate the influence of particle size and (2) examined other laboratory aggregate tests. To evaluate the influence of particle size the same NCAT testing protocol with TWPD conditioning, DFT friction testing, and CTM macro-texture testing procedures was used. LAB-2 evaluated bauxite, taconite, flint and steel slag, but the source of each aggregate type was not intentionally tied to LAB-1 aggregate sources. The HFST aggregate samples were screened to test No. 6 sieve, No. 8 sieve, No. 12 sieve, and No. 16 sieve particles independently. TWPD slabs were prepared for all four particle sizes. DFT friction and CTM texture measurements were taken before conditioning and after 70,000 and 140,000 cycles of TWPD conditioning. Random conditioning and testing protocols were applied and the quality of the test measurements was evaluated and found acceptable.

The surface macro-texture response from the particle size evaluation was consistent with LAB-1. The CTM measured some texture reduction after the first period of TWPD conditioning but no change after the second period of conditioning. As expected, the HFST surface macro-texture decreased as the size of the aggregate particles decreased. Surfaces with No. 6 sieve particles measured 2.2 mm MPD and surfaces with No. 16 sieve particles measured 1.1 mm. The friction response showed a similar trend during conditioning. Friction reduced after the first period of TWPD conditioning and did not change after additional conditioning. The terminal DFT(40) friction values for all four aggregates reacted similarly to the differences in particle size. There was marginal change in measured friction for surfaces with No. 12 and

No. 8 particles. Friction reduced for surfaces with either No. 16 or No. 6 particles. The evaluation of macro-texture and friction combined showed friction increased as macro-texture increased up to a MPD of 2.0 mm. Friction decreased on the conditioned slabs with MPD above 2.0 mm.

The second objective of LAB-2 used the Micro-Deval device to condition the aggregates and the second generation Aggregate Image Measurement System Model AFA2A (AIMS) to measure the aggregates. This second objective planned to include the British Wheel and British Pendulum, but attempts to modify the test specimen preparation for small HFST aggregate particles was unsuccessful. The same four LAB-2 aggregate sources were used. Only the No. 8 sieve particles were used for this second study objective. The AIMS measurements were taken before conditioning and after 25 and 50 minutes of Micro-Deval conditioning. A random sequence of conditioning and testing protocol was applied and the quality of the test measurements was evaluated and found acceptable.

The aggregates showed differences in Micro-Deval mass loss but none of the aggregates reached a terminal mass loss. Mass loss results ranked bauxite as the best performer and taconite as the lowest performer. The rank order of the mass loss results agreed with the DFT(40) friction results, except flint aggregate ranked second for mass loss and fourth (last) for friction. The AIMS measurements quantified the shape of all four aggregates in a narrow range of 6 to 8 on a scale of 0 to 20 and there was very little change in particle shape after Micro-Deval conditioning. Particle shape did not correlate to friction, so shape was not given further consideration. The AIMS angularity test results showed bauxite and taconite are very similar. The flint sample had a higher mean angularity and the slag aggregate had the highest angularity. The anticipated trend would be higher angularity achieves higher friction, but actual LAB-2 results show no correlation between particle angularity and DFT friction. Overall, the use of Micro-Deval and AIMS to condition and measure aggregate characteristics did not correlate to the aggregates' friction measurements.

The final step of the project compared the data sets from all three studies to determine if there were any correlations. This analysis made the following observations:

- Terminal LAB-1 CTM surface texture had a reasonable correlation (R^2=0.88) to terminal FIELD CTM texture based on all eight aggregates.
- Terminal LAB-1 DFT friction had a good correlation (R^2=0.95) with FIELD DFT friction when silica sand was removed from the data set.
- Terminal LAB-1 DFT and FIELD DFT had very good correlation (R^2=0.99) with FIELD skid trailer friction based on three aggregates after extended conditioning. Both LAB-1 and FIELD DFT measurements were consistently higher than the skid trailer measurements.
- There is no clear correlation when the combined surface texture and friction results are compared. A general trend is observed if bauxite and silica sand data is removed.
- None of the seven alternative aggregates matched the friction performance of the bauxite.
- The CTM surface texture of LAB-2 No. 12 sieve screened particles had the closest match to the surface texture of LAB-1 blended HFST aggregate (MPD=1.5 mm).

- The DFT friction for LAB-1 and LAB-2 ranked the same for bauxite, taconite, and flint. LAB-2 Colorado steel slag friction (DFT(40)=0.90) performed much better than LAB-1 Pennsylvania steel slag (DFT(40)=0.49).
- The combined surface texture and friction results for LAB-1 and LAB-2 were similar to the results from FIELD but the laboratory friction is offset higher.

The series of three studies had the following conclusions and recommendations:

- All eight surfaces maintained good macro-texture (predominately MPD > 1.0 mm) when compared to typical conventional asphalt dense-graded mix macro-texture values below 0.5 mm.
- The eight surfaces measured terminal DFT(40) values in the range of 0.84 to 0.49 in LAB-1 and 0.79 to 0.43 in FIELD.
- Locked wheel skid trailer friction measurements (SN40R) over the last 1.5 years of field conditioning decreased from 70 to 64 on bauxite, decreased from 55 to 43 for flint, and decreased from 55 to 40 for granite.
- Terminal surface characteristics were achieved after early conditioning (less than one month for FIELD friction) both in the laboratory and in the field. The terminal texture and friction characteristics decreased very slowly during additional conditioning.
- For each aggregate tested in LAB-2, the surface with MPD of 1.50 to 2.00 mm measured the highest DFT(40) friction.
- There may be a correlation between HFST surface friction and Micro-Deval mass loss based on three of the four aggregates.
- There was no correlation between HFST surface friction and AIMS particle shape and angularity.
- An additional laboratory procedure is needed to prepare test specimens of small aggregate particles (retained on No. 8 sieve) for the British Wheel and Pendulum friction test.
- There is no correlation between HFST surface macro-texture and friction.
- Lab conditioning with the NCAT TWPD was less aggressive than field abrasion.
- A DFT measures higher friction values than a locked-wheel skid trailer.
- Measured friction for alternative HFST aggregates was not equal to bauxite.

Further study

Further research is needed to separately measure the influence of pavement surface macro-texture and aggregate surface micro-texture on crash rate potential. In this study, standard friction testing with a locked-wheel skid trailer is used as an objective measure to correlate/predict crash rate potential (i.e., higher pavement surface friction has shown to reduce crash rates). Macro-texture and micro-texture each influence the crash rate potential. However, the relative degree to which macro-texture and micro-texture influence the crash rate potential is not documented, particularly at critical locations where HFST are typically placed. This further research could determine if common friction aggregates (high quality, good micro-texture) used in the U.S. combined with HFST pavement surface high macro-texture would reduce crash rates comparable to HFST with bauxite.

INTRODUCTION/BACKGROUND

The Federal Highway Administration (FHWA) Roadway Departure Safety Program includes guidance and tools to address crashes on wet pavement. Pavement friction is one component of the program and one of the tools is High Friction Surface Treatments (HFST). An HFST is an important application for critical safety locations like bridge decks, horizontal curves, and high speed deceleration ramps.

FHWA worked jointly with American Association of State Highway and Transportation Officials (AASHTO) and American Traffic Safety Services Association (ATSSA) to develop a HFST Guide Specification (PP 79-14 Standard Practice for High Friction Surface Treatment for Asphalt and Concrete Pavements). Currently the guide specification only recognizes calcined bauxite aggregate. (FHWA 2013, FHWA 2014) Therefore the AASHTO definition for HFST requires calcined bauxite.

HFST began in the early 1950's in the USA as a thin polymer bonded bridge deck treatment. The industry that has installed this product for many years have used a variety of aggregates which they feel has performed well. The product was adopted for use in the UK and began to use calcined bauxite for roadway conditions applied on asphalt pavements as well as concrete. The safety benefits of the polymer overlay system using calcined bauxite were first published in 1976 showing astounding crash reductions for intersections. They showed a 31% crash reduction for 800 intersections in the Greater London Area.

While this concept was being successfully used in other countries for crash reduction and similar products were being used in the USA on bridges, the FHWA Office of Pavement Technology initiated the Surface Enhancements at Horizontal Curves program to demonstrate the application of High Friction Surface Treatments (HFST) in roadway curves. When the demonstration program began, AASHTO had not written the guide specification for HFST and the companies that bid the demonstration projects often bid their thin polymer bonded bridge deck treatment systems which did not always include calcined bauxite.

HFST require high friction values and resistance to aggregate polishing to address the extreme friction demand created by the geometric conditions in curves and high speed decelerating traffic. Pavements exposed to continuous excessive friction demand may have accelerated aggregate polishing which can lead to a skid concern. At this point FHWA and AASHTO view HFST as a specialized subset of thin-bonded polymer overlays for locations with critical friction demand. Calcined bauxite has a proven crash reduction record. The question that needed to be answered was there other regionally available and less expensive friction aggregates that can perform an equal or near equal service.

Bauxite is mined in many countries, but the USA produces less than 1 percent of the product. The large majority of bauxite ore is used for the production of aluminum. Smaller amounts are used in chemical processes, industrial abrasives, and in the refractory industry. The suppliers of calcined bauxite for the refractory industry are the primary source for the calcined bauxite used for HFST. The amount used for HFST is a small fraction of the calcined bauxite produced for the Refractory industry in the USA.

In the USA, the majority of calcined bauxite is imported from China. The calcination cost, crushing requirements, and transportation cost make bauxite a more expensive product compared to other aggregates. It is the calcination process to Refractory Grade specifications that give the aggregate the characteristics that create excellent wear resistance. In essence it is an artificial aggregate designed for durability in the refractory industry. As a point of reference, common calcined bauxite HFST specifications call for LA Abrasion loss less than 10% and field skid resistance values greater than 64 SN40R (ATSSA, AASHTO 2014).

Comparative field testing of alternative aggregates for HFST friction performance is not practical. The ideal test site requires a single long horizontal curve, and the location and length of each test section must accommodate consistent locked wheel skid trailer testing and uniform traffic abrasion. There are very few sites that would meet these comparative testing criteria. Most of those sites operate under high risk traffic conditions and should not be used for testing potentially marginal alternative materials. If multiple sites are needed, it is difficult to find sites with similar traffic, climate, and winter maintenance.

The National Center for Asphalt Technology (NCAT) Pavement Test Track and NCAT Three Wheel Polishing Device (TWPD), as shown in Figure 1, offer a practical and technically sound controlled evaluation of alternative HFST aggregates. Neither the test track nor lab evaluation is a true field traffic examination of performance, but these methods permit a direct comparison of alternative aggregates to the standard bauxite by applying uniformly controlled conditioning and testing.

Figure 2 depicts a generic pavement friction performance curve for an asphalt pavement. The early portion of friction performance exhibits a dramatic increase in friction as the asphalt binder film wears off the pavement surface followed by a steep friction loss due to initial aggregate polishing. For the NCAT Pavement Test Track, these friction changes occur from initial construction to approximately 2 million (2M) ESALs of truck traffic wear, about five months. After the initial aggregate polishing, the surface friction performance stabilizes as defined by long-term friction loss trend, commonly called terminal friction. For HFST, the surface begins with peak friction because there is no asphalt binder film coating the aggregate. This study focused on the long-term friction loss trend (terminal friction) of each HFST aggregate.

Figure 1 NCAT Three Wheel Polishing Device

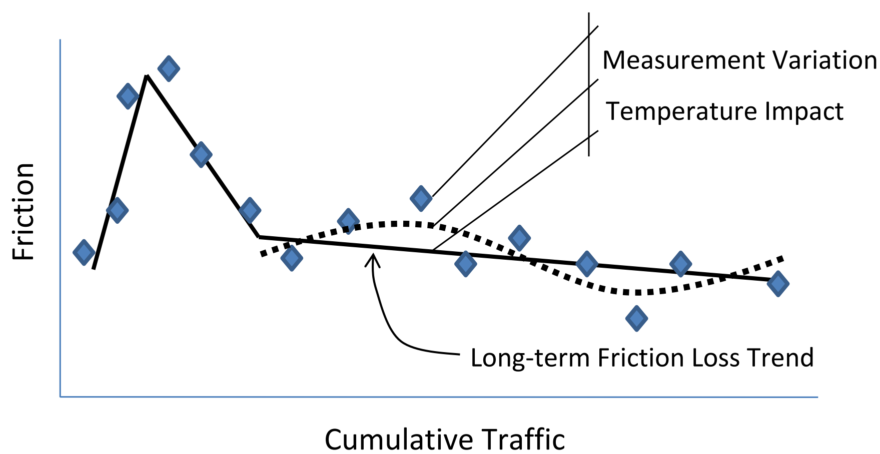


Figure 2 Generic Asphalt Surface Friction Performance Curve

SCOPE of STUDY

For purposes of this study the terms bauxite and HFST are used generically and do not fully agree with the recently adopted AASHTO standard practice (PP 79-14) discussed in the Introduction above. While the term bauxite refers to a natural aggregate with relatively soft properties, in this report calcined bauxite will be simply referred to as bauxite. In this report, the term HFST will be used to describe the placement of a thin polymer bonded friction aggregate surface treatment to improve the friction properties of the pavement surface. As such, the term HFST does not meet all the criteria of PP 79-14.

This study was divided into three components. The first two components were a direct comparison of eight aggregates applied as HFST. The first component was a laboratory evaluation (LAB-1 study) and the second component was a test track evaluation (FIELD study). The third component was a more detailed laboratory evaluation of four selected aggregates (LAB-2 study). The use of the TWPD for surface friction comparisons in the laboratory is an analysis process that is still developing. Since there are no specified standards or thresholds for friction values, this test procedure allows engineers and researchers to make relative comparisons of friction performance between surfaces. It will be the responsibility of governing agencies to determine what an acceptable threshold should be. For purposes of this study, the bauxite was considered the control aggregate.

The scope of LAB-1 was to determine if there are aggregates from sources in the United States that provide adequate HFST friction performance. The objective was to evaluate the friction performance of seven alternative HFST aggregates and the control bauxite aggregate using identical conditioning (polishing) with the NCAT TWPD. The description and source of the aggregates are given in Table 1. The table also gives other names for these aggregates. Some portions of this report refer to these alternative names.

Table 1 Study Aggregate Types and Sources

Aggregate Type	Source	Other Aggregate Names
LAB-1 Study and FIELD Study		
Granite	*Wisconsin*	
Bauxite	*China*	*calcined bauxite*
Flint	*Picher, Oklahoma*	*chert, chat*
Basalt	*Washington*	
Silica	*Ohio*	*silica sand*
Slag	*Mechanicsburg, Pennsylvania*	*steel slag*
Emery	*Halsey, Oregon*	*alumina-ferrous oxide*
Taconite	*Minnesota*	
LAB-2 Study		
Bauxite-2	*China*	*calcined bauxite*
Flint-2	*Picher, Oklahoma*	*chert, chat*
Slag-2	Colorado Springs, Colorado	*steel slag*
Taconite-2	*Minnesota*	

The scope of FIELD was also to determine if there are aggregates from U.S. sources that provide adequate friction performance as part of a HFST. The objective was to evaluate all eight aggregates as

HFST on the NCAT Pavement Test Track. The field sections were placed to evaluate the performance of the seven alternative aggregates and bauxite control under identical field traffic conditioning. The limitations of FIELD were the length of each test section, a limited period of trafficking, and restrictions on the types of friction tests. These will be explained in more detail later in the report.

The scope of LAB-2 addressed two questions raised during LAB-1 and FIELD. First, does the depth of macro-texture of the surface influence the measured friction values? Second, are there laboratory tests for aggregate that correlate to HFST friction performance? The first question was raised because there was no intent to control the gradation of the aggregate samples in LAB-1 and FIELD studies. As such, the surface macro-texture varies with the gradation of each aggregate. In LAB-2 the friction performance was evaluated using HFST surfaces with controlled aggregate gradations. The second question was raised to explore other aggregate tests that may be used to qualify aggregate samples for HFST. The second part of LAB-2 scope was to determine if there are simpler laboratory tests that highway agencies can specify for HFST aggregate.

This report describes the results of each study component separately, followed by a correlation between the results.

LAB-1 STUDY

Sample Preparation

The eight HFST aggregates were placed on 20x20 inch asphalt test slabs. Three replicate slabs were made for each alternative aggregate. The same installation crew that placed the HFST sections on the NCAT Pavement Test Track for FIELD placed the HFST on each test slab for LAB-1. The slabs were prepared on the same day the corresponding HFST sections were installed on the Test Track. The same epoxy bonding agent, used in the POLY-CARB SAFE-T-GRID system (DOW POLY-CARB website), and aggregates supplied for the Test Track installation were applied to the test slabs. The application method was similar to the track placement. The epoxy was placed and spread on the slab, and the aggregate was broadcasted by hand onto the uncured epoxy surface. After the epoxy cured 24-hours, the excess aggregate was swept off and the slabs were transported to the NCAT laboratory.

Test protocol

The laboratory protocol for the NCAT TWPD is a developing procedure. The NCAT TWPD was initially developed at NCAT in a 2004-2006 study (Vollor and Hanson 2006). A second study completed in 2010 refined the test parameters and found a reasonable correlation between laboratory results and field tests (Erukulla 2011). The TWPD is designed to uniformly condition (polish) a 284 mm diameter path on the surface of a test slab.

The conditioned path is tested by ASTM test methods E 2157 (*Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter*) and E 1911 (*Standard Test Method for Measuring Paved Surface Frictional Properties Using the Dynamic Friction Tester*), commonly called the Circular Texture Meter (CTM) and Dynamic Friction Tester (DFT), respectively. The CTM and DFT are used for measuring the surface texture and friction of pavement surfaces. Both test methods can be used in the laboratory or in the field. The CTM measures the pavement surface macro-texture profile and provides a mean profile depth (MPD) in millimeters to quantify the macro-texture. The DFT measures pavement surface friction properties as a function of speed (0, 20, 40, 60, and 80 km/h for this study) and provides a dimensionless value called the friction number (Fn). There is no consistent trend that higher DFT speed measures higher friction, so the speed that produces the most repeatable measure, 40 km/h, was used for the entire study. In this report, the DFT friction values are commonly expressed as DFT(40), meaning the Fn at 40 km/h. For both test procedures, increasing values indicate higher surface friction characteristics.

Prior to installing the alternative HFST aggregates on the slabs, the perimeter of each slab was taped to provide a neat edge for the HFST. Later, this proved to be a problem because the rubber feet of the DFT straddled the HFST, which was 5-6 mm higher than the slab surface. A proper DFT test could not be performed due to this offset height of the HFST surface. The DFT test is designed to contact the test surface when it is flush with the rubber feet and the DFT spring support provides the correct normal load. The higher HFST surface reduces the spring extension, increasing the normal load during the test. The problem was resolved by mounting rubber feet on the DFT that were 5 mm taller.

For the evaluation of HFST aggregates in LAB-1, the following test protocol was used.

- The three replicate slabs of each HFST aggregate were divided into three test groups. Each group of eight slabs included one slab for each HFST aggregate. Two groups were conditioned and tested. The results of the two groups were compared for consistency. If the results were determined to be consistent, then the third group of slabs was not tested. If the results were determined to be inconsistent, then one or more slabs from the third group were tested.
- A new set of three TWPD tires was installed for each group of eight slabs. The TWPD was operated at 60 rpm, 50 psi tire pressure, and 91 lb gross carriage weight. Previous studies using the TWPD showed that 80,000 to 100,000 (80K to 100K) conditioning cycles were needed to reach a terminal surface friction condition. This study extended the polishing to 140K cycles to help distinguish performance between the higher quality aggregates.
- Each CTM test included five replicate measurements. A template was placed over each test slab to ensure that all CTM tests were performed on the same circular path.
- Each DFT test included three replicate measurements. A template was used to ensure the measurements were taken at the same location. DFT rubber slider pads were replaced after testing four slabs. Each set of rubber slider pads was used for a total of twelve measurements as specified by the ASTM standard. As discussed earlier, the perimeter of the HMA slab surface was not covered with the HFST material. The corners of the slab support the DFT and CTM. To account for the difference in height, the rubber feet supporting the DFT were replaced with slightly higher feet.
- The sequence of DFT-CTM testing and NCAT TWPD conditioning was as follows:
    1. One group of eight slabs was randomly ordered for testing and conditioning.
    2. Initial CTM and DFT measurements were taken on each slab in the established order.
    3. TWPD conditioning for 70K cycles was performed on each slab in the group following the same order.
    4. The group of eight slabs was randomly re-ordered for testing and conditioning.
    5. CTM and DFT measurements were taken on each slab as re-ordered.
    6. An additional 70K cycles of conditioning was performed for each slab in the group following the same re-order.
    7. The group of eight slabs was randomly re-ordered for testing.
    8. Final CTM and DFT measurements were taken on the group of slabs as re-ordered.
    9. Repeat the test protocol sequence for the second group of eight slabs.

<u>Test Results</u>

The DFT and CTM measurements of the laboratory study are listed in Table 2 and presented as graphs in Appendix A of this report. Each graph in the appendix represents the result of testing two slabs of each test aggregate.

During the polishing, a significant loss of tire rubber was observed. Figure 3 shows an example of loose tire rubber on a test slab. Smaller amounts of rubber debris have been noted in other studies with surfaces that had high friction characteristics. The loose rubber was removed from the test surface before CTM and DFT testing. At the end of polishing each group of eight slabs for 140K cycles each (1,120K total cycles), the tires were severely worn, as shown in Figure 4. As specified in the test protocol, the tires were replaced for each group of eight slabs.

Figure 3 Photo of TWPD Tire Rubber Debris on Test Slab

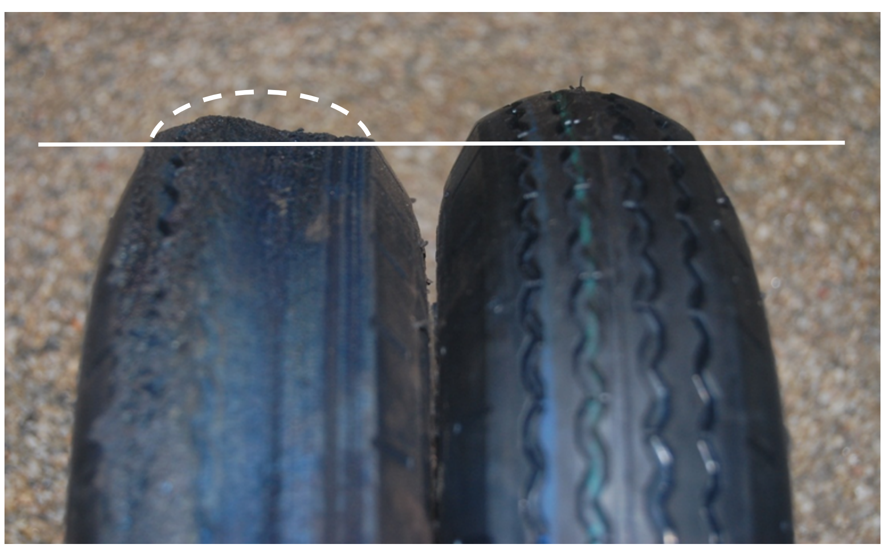


Figure 4 Comparison of New and Worn Tire

Table 2 Summary of LAB-1 DFT and CTM Results

Test Method	DFT(40)			CTM (MPD mm)		
TWPD cycles	**0**	**70K**	**140K**	**0**	**70K**	**140K**
Aggregate Type						
granite	0.88	0.59	0.57	1.83	1.49	1.46
bauxite	0.98	0.88	0.81	1.97	1.44	1.37
flint	0.88	0.65	0.60	2.17	1.61	1.52
basalt	0.90	0.70	0.62	2.18	1.53	1.57
silica	0.73	0.53	0.49	2.12	1.67	1.66
slag	0.69	0.51	0.47	1.51	1.17	1.14
emery	0.98	0.66	0.62	1.97	1.39	1.36
taconite	0.78	0.73	0.67	2.34	1.60	1.52

Test Quality Control

Laboratory testing consisted of 48 sets of DFT and CTM measurements (three cycle periods times two slabs times eight materials). Only the data from DFT measurement speeds of 20 kph, 40 kph, and 60 kph (DFT(20), DFT(40) and DFT(60) respectively) were considered in the data quality control (QC) analysis. DFT(0) and DFT(80) results are typically much more variable and were not used in the analysis. Testing quality control examined the three replicates of DFT measurements. The ASTM test standard precision states that the DFT has a standard deviation of 0.044 to 0.038 for eight replicate tests for the recorded friction at 30 km/h and 60 km/h, respectively. For three replicate tests, the evaluation of the range is more appropriate than computing the standard deviation. The histogram of DFT three-replicate ranges from all sets is shown in Figure 5. A nominal precision for the range between eight replicate measurements would be 0.120 (+/- 1.5 standard deviations X 0.040). The testing of the HFST slabs was based on only three replicates, so the precision would have an allowable range higher than 0.120. The Figure 5 bar chart shows that 65% of the tests had a range below 0.040 and 98% of the range values fell below 0.120, which was well within the precision criteria. The two largest range values were 0.121 and 0.151. A coefficient of variation for the DFT measurements, based on the range value in place of the standard deviation value, is less than 5% for 87% of the data sets.

The data sets for five replicates of CTM measurements were examined for data quality control. The histogram of ranges from all sets is shown in Figure 6. The ASTM standard precision states that the CTM has a standard deviation of 0.03 for eight replicate tests. The testing of the HFST was based on five replicates, so the measurement precision would have an allowable range of 0.117 based on ASTM C670 criteria for a 0.03 standard deviation. The Figure 6 bar chart shows that 77% of the tests had a range below 0.12 and 6% of the ranges were above 0.18 (+/- 3.0 standard deviations). Three data sets fell well above the ASTM criteria with ranges between 0.18 and 0.38. The five replicate values in these data sets were within two standard deviations of the mean, so there were no outliers. The coefficient of variation for the CTM measurements is less than 5% for 98% of the data sets.

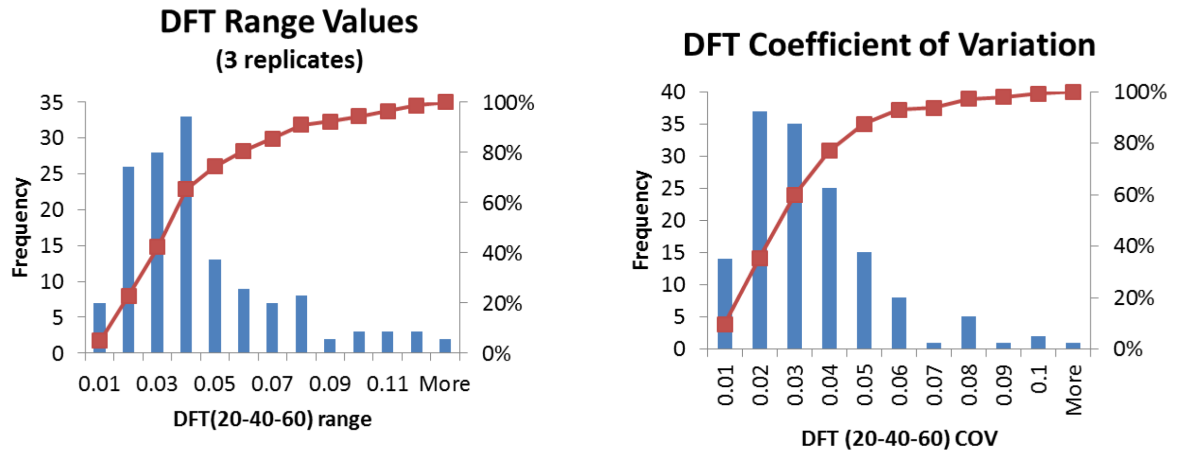


Figure 5 DFT Data Quality Control Histograms

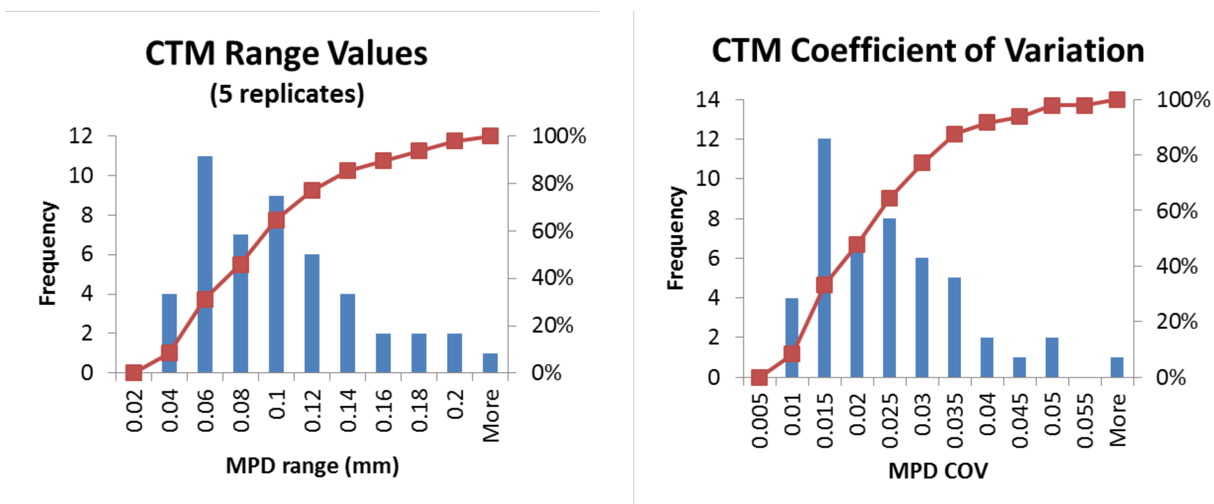
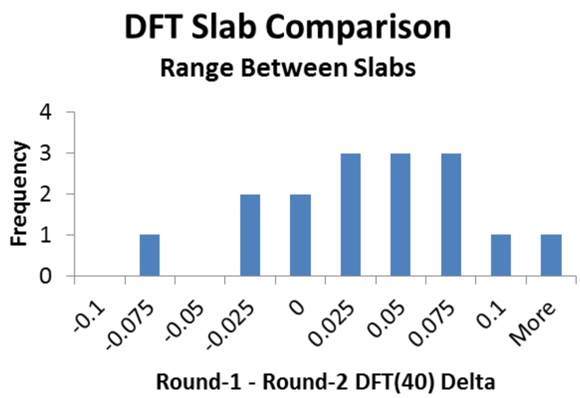


Figure 6 CTM Data Quality Control Histograms

The second level of the quality control is determining if the two slabs for each HFST aggregate generated similar results. If the results are similar, the third replicate slab is not required. The average DFT(40) results from 70K cycles of TWPD in Round-1 testing were compared to the same results of Round-2 testing. The same comparison was made for the 140K cycle test results. Differences between the Rounds were combined into a histogram to show the distribution of slab test differences, shown in Figure 7. Overall, the average difference was a DFT(40) delta of 0.035. The maximum differences were approximately two standard deviations from the average and none of the deltas were more than 8% from the average. This analysis was sufficient to conclude that testing the third slab was not required. A similar analysis was conducted for CTM test results between Round-1 and Round-2. The results were comparable to the DFT results, so testing the Round-3 slabs was not performed.



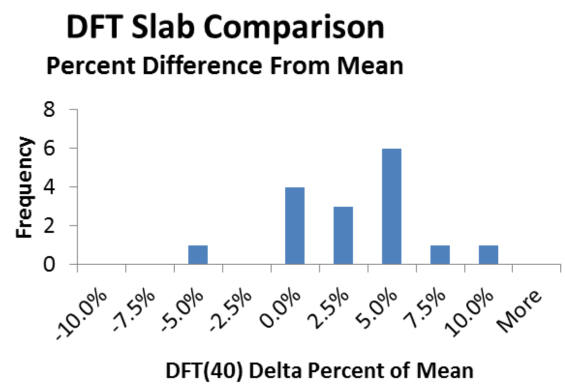


Figure 7 Slab Replicate Comparison for DFT(40) Values

<u>Data Analysis</u>

This first study compared the laboratory performance of eight different HFST aggregates. More specifically the analysis focused on the terminal (70K and 140K cycles) characteristics of the surfaces. The analysis also looked at the change in values between each measurement increment. The comparison of the change in test measurements between 70K cycles and 140K cycles is particularly important to determine the rate each aggregate was still polishing.

Figures 8 and 9 used bar charts to display the relative difference in the change in CTM and DFT values as the samples were conditioned. For this analysis, the relative differences are expressed as percent loss between the values. Surface texture (CTM) loss of 20 to 30% occurred during the first 70K cycles of TWPD conditioning for all eight aggregates. Texture loss after the second conditioning period was 3% or less for granite, basalt, silica sand, slag, and emery; and less than 6% for bauxite, flint, and taconite. For all practical purposes, there was no change in surface texture after 70K cycles. Based on these trends, the terminal CTM values were computed as the average of the values measured at 70K and 140K TWPD conditioning cycles.

Friction (DFT) loss after 70K conditioning cycles spanned a broader range of 10 to 30%. Bauxite lost 11% and the other aggregates were above 20% loss. After the second conditioning period, six of the aggregates lost an additional 6 to 8% friction. The smallest loss was granite (4%) and the largest loss was basalt (12%). Since a majority of the aggregates had similar friction loss between 70K and 140K cycles, it was determined that the average of the values measured at 70K and 140K would be used as the terminal friction value for this first laboratory study.

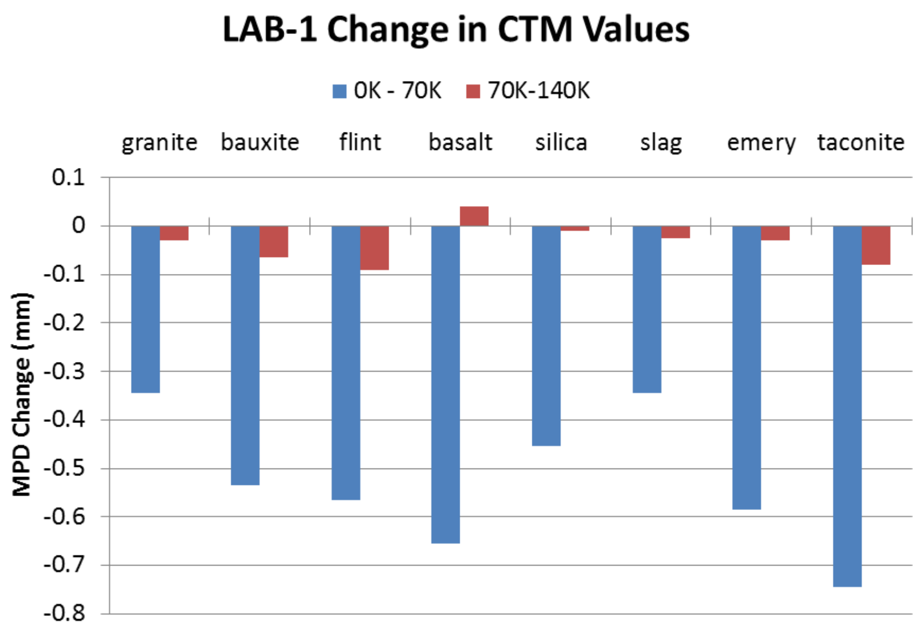


Figure 8 Change in Surface Texture during TWPD Conditioning

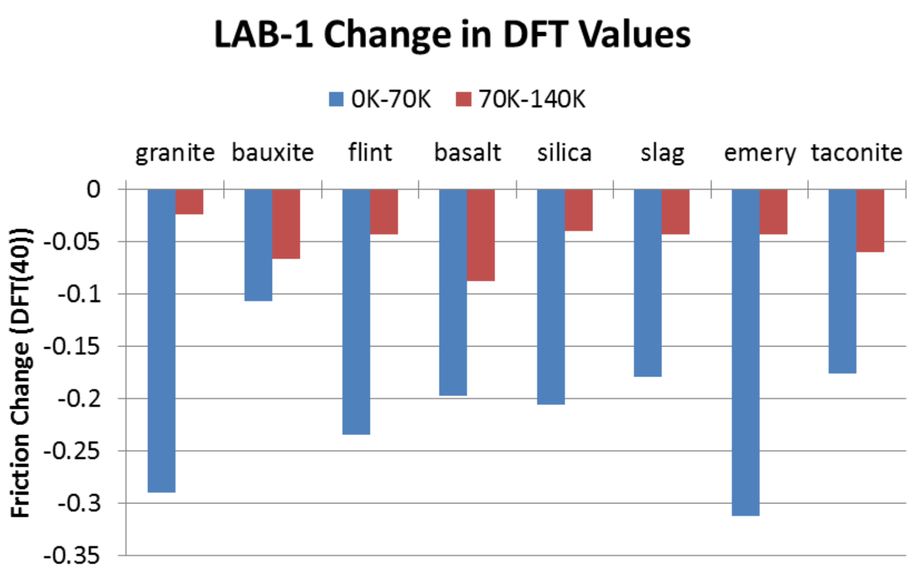


Figure 9 Change in Friction during TWPD Conditioning

Figure 10 shows the computed terminal texture and friction values for the first laboratory study. The chart is organized in rank order based on the composite average DFT(40) friction values for each aggregate. The intent of this study was to determine if regionally available friction aggregates could match the friction performance of bauxite. This summary chart of the terminal values shows that none of the seven alternative HFST aggregates provided friction comparable to bauxite based on the DFT measurements. Four aggregates (taconite, basalt, emery, and flint) maintained terminal friction values above 0.60. Two aggregates (silica sand and slag) measured terminal values at or below 0.50.

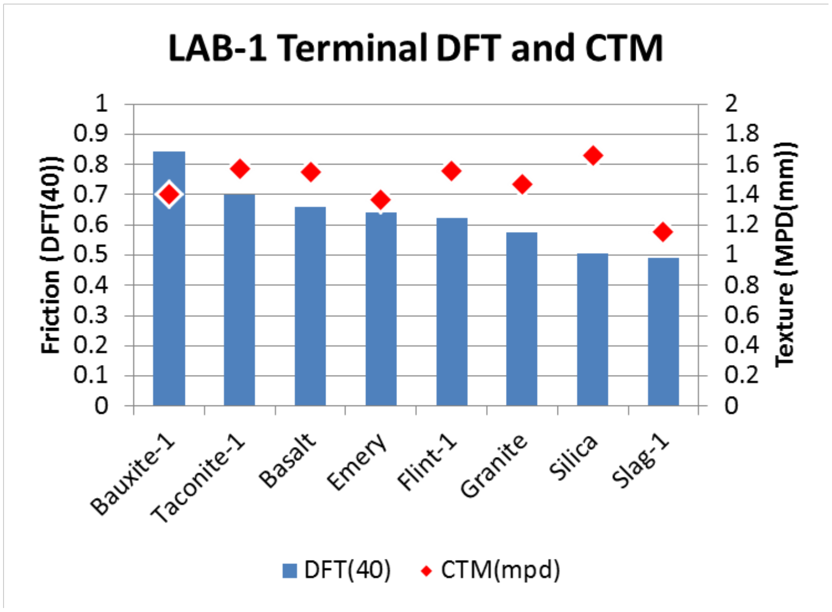


Figure 10 Summary of LAB-1 Terminal Results

The terminal surface texture values in Figure 10 indicate that all of the HFST, except slag, maintained surface macro-texture values at or above 1.4 mm. Even though bauxite measured the highest DFT friction values, the bauxite surface texture was lower than most of the group. All of the surface texture values were much higher than conventional dense graded asphalt mixtures, which commonly measure MPD in the range of 0.30 to 0.50 mm. All eight HFST surfaces would be expected to provide a significant reduction in vehicle tire hydroplaning. The data also shows no correlation between the terminal friction and terminal surface texture.

FIELD STUDY

Field Test Section Location and Placement

FIELD used two standard 200-ft long research sections with a 12-ft lane width located in the western curve of the NCAT Pavement Test Track. The super-elevated curve was selected to place both direction of traffic and transverse tire interactive force on the test surfaces. The first research section, W8, was divided into two equal sub-sections (A and B). The second research section, W9, was divided into six sub-sections (A – F). Sub-section W9A was placed on half of Section W9 and the remaining five HFST aggregates were placed as short 15-ft sub-sections. A different HFST aggregate was applied to each sub-section. Table 3 shows the sub-sections and HFST aggregate placed in each test section. Test section W8A was terminated at 85 ft because there was insufficient granite aggregate to complete the entire 100-ft length.

Table 3 NCAT Test Track HFST Sub-Section Locations

Test Track ID #	HFST aggregate	Subsection length (ft)
W8A	granite	85
W8B	bauxite	100
W9A	flint	100
W9B	basalt	15
W9C	silica	15
W9D	slag	15
W9E	emery	15
W9F	taconite	15

On April 17, 2011, a HFST contractor installed all eight test sections on the track. They used a Dow Chemical Company – POLY-CARB two-part polymer bonding agent for all of the HFST aggregates. Each HFST test section was outlined with wide tape before the installation began. The polymer bonding agent was mixed, poured, and spread over each HFST test section, and immediately followed by manually broadcasting the aggregates onto the surface. The tape outlining each test section was removed after installation. After an initial two-hour cure period, a compressed air hand tool was used to blow excess aggregate off each surface. The HFST test sections were allowed to cure for 36 hours before the controlled truck traffic was restarted.

Test Protocol

FIELD used controlled truck traffic conditioning and three test methods. The installation was placed in the last quarter of the two-year Pavement Test Track traffic loading cycle. The controlled traffic is five heavily loaded triple trailer trucks consisting of an 11 kip steer axle, 42 kip tandem axle, and five 21 kip single axles. The HFST test sections were subject to approximately 2.6M ESALs (equivalent to 350,000 18-wheel tractor-trailer units) in six months. The three long HFST test sections (W8A, W8B and W9A) were conditioned with additional controlled truck traffic from October 2012 to April 2014 to reach 10M ESALs.

For CTM and DFT measurements, each test section was divided into three sublots, 25-ft sublots for long sections and 5-ft sublots for short sections. A test location was randomly selected within each sublot along the left wheel path. At each test location three replicate CTM and DFT measurements were taken. The final CTM and DFT value for each test section on a specific test date was the average of nine measurements. The DFT rubber slider pads were replaced prior to testing on each test section and were used for nine drops (measurements). The planned testing frequency for CTM/DFT measurements was every month, although actual testing frequency was dependent on Test Track availability, weather conditions, and equipment and staff availability.

Friction measurements with the full-scale locked-wheel skid trailer (ASTM E274-11 *Skid Resistance of Paved Surfaces Using a Full-Scale Tire*) were limited to the three 100-ft sections. It was not possible to isolate a skid trailer friction measurement on the short 15-ft sections. The skid trailer traveled at 40 mph for testing, which created a 59-ft test for each 1.0 second locked-wheel duration. The specified ribbed test tire was mounted on the left side of the trailer. HFST test sections were also included in the broader NCAT Pavement Test Track skid trailer testing protocol. The skid trailer makes multiple passes around the track to accumulate three replicate measurements on each section. The final skid trailer value for each test section on each test date was the average of three measurements. The planned testing frequency was every month, although actual test frequency was subject to the availability of the skid trailer, which was operated by the Alabama DOT.

Test Results

The first set of CTM/DFT friction tests was conducted on April 25-26, 2011, one week after the installation of the HFST test sections and shortly after traffic was started. Four additional sets of tests were made before the end of the truck traffic conditioning cycle in October 2011. Post-traffic testing was conducted in early November, 2011 and again in January, 2012. Traffic conditioning and friction testing resumed in October 2012 for sections W8A, W8B, and W9A when the Test Track initiated the 2012 cycle of research. For the additional conditioning and testing, the CTM/DFT testing frequency was reduced to every three months.

The first set of skid trailer measurements was conducted on May 9, 2011. Unfortunately, lack of instruction to the skid trailer crew on the location of the HFST test sections made the May 9 data questionable. The Alabama DOT skid trailer was not able to return to the Test Track until after the end of the truck traffic conditioning. Post 2M ESALs skid trailer friction measurements were taken in late December 2011 and late January 2012. Consistent skid trailer testing was achieved when the Pavement Test Track initiated the next research cycle in October 2012. Twelve additional tests were conducted between November 2012 and April 2014 as the three test sections reached 10M ESALs.

Table 4 is a summary of the average test values for each HFST test section at each test increment. The test increment is expressed as cumulative ESALs used by the Pavement Test Track for traffic conditioning.

Table 4 Test Track Field Data

CTM							
ESAL (millions)	0	0.4	0.8	1.4	1.8	2.6	2.6
W8A granite	1.64	1.41	1.63	1.17	1.16	1.25	1.38
W8B bauxite	1.41	1.22	1.23	1.15	1.13	1.24	1.14
W9A flint	1.74	1.62	1.46	1.33	1.39	1.40	1.37
W9B basalt	1.67	1.67	1.55	1.51	1.43	1.43	1.46
W9C silica	1.85	1.74	1.56	1.55	1.54	1.39	1.41
W9D slag	1.49	0.94	0.90	0.84	0.86	0.70	0.72
W9E Al-Fe Oxide	1.56	1.47	1.31	1.31	1.21	1.21	1.26
W9F taconite	1.85	1.78	1.72	1.69	1.56	1.55	1.58

DFT(40)														
ESAL (millions)	0	0.4	0.8	1.4	1.8	2.6	2.6	3.2	4	4.6	6.6	7.2	9	11.4
W8A granite	0.61	0.46	0.51	0.48	0.48	0.51	0.59	0.53	0.50	0.53	0.38	0.48	0.51	0.43
W8B bauxite	0.92	0.75	0.76	0.78	0.81	0.83	0.86	0.85	0.82	0.84	0.69	0.74	0.89	0.75
W9A flint	0.67	0.55	0.54	0.52	0.58	0.60	0.62	no data	no data	0.58	0.52	0.51	0.59	0.50
W9B basalt	0.67	0.51	0.54	0.52	0.56	0.56								
W9C silica	0.61	0.56	0.55	0.53	0.55	0.57								
W9D slag	0.52	0.42	0.43	0.41	0.43	0.45								
W9E Al-Fe Oxide	0.73	0.51	0.53	0.53	0.56	0.58								
W9F taconite	0.75	0.57	0.61	0.58	0.62	0.65								

Skid Trailer															
ESAL (millions)	0	2.6	2.6	2.7	4.2	4.9	5.9	6.3	6.9	7.2	8.5	8.9	9.3	9.7	10.1
W8A granite	no data	57.0	52.4	57.1	52.5	50.0	45.7	44.1	44.7	48.3	38.1	40.8	47.4	41.8	40.7
W8B bauxite	no data	72.4	70.9	65.4	54.3	70.9	66.5	65.6	65.8	67.2	60.8	61.8	48.7	67.9	64.2
W9A taconite	no data	56.2	58.1	55.7	47.7	50.8	48.1	48.3	47.8	50.2	41.7	41.1	45.2	47.1	44.2

Test Quality Control

The primary purpose of the test quality control effort was to identify and address outlier data. The second purpose was to examine the data for possible testing equipment errors. The sets of data for FIELD were different for each test. There were 196 sets of data used for the DFT analysis, 133 sets of data used for the CTM analysis, and 42 sets of data used for the skid trailer analysis. In every case each set of test data was composed of three replicate test measurements. For the CTM and DFT testing, there were multiple measurement locations for each HFST test section. For the skid trailer, there was only one set of three replicate tests for each HFST test section.

Field testing adds variability to the measured data. The CTM and DFT test locations were randomly selected for each set of tests. This increased variation due to physical differences along the pavement surface. The offset from centerline for CTM and DFT testing was held constant, but there was no control over the location of each tire pass. The only differences as the HFST test sections were installed were section length and aggregate type. Air temperature, tire temperature, and pavement surface temperature influence the DFT and skid trailer measurements and varied over the testing period. The cleanliness of the pavement surface was a variable for the skid trailer, although the high macro-texture of the HFST should have diminished this influence.

The quality control check on CTM data was based on the range of the measurements for each test section. Sections with three replicate tests at three sublot test locations generated a nine-point data range. Sections with three replicates at two test sublot locations generated a six-point range. When the HFST test sections were measured as part of testing all Test Track sections, the range values were part of a large distribution of range values representing over 46 test sections. When the HFST test sections were measured separate from the Test Track sections, the range distribution set was only eight values, which was insufficient for a range distribution evaluation. Figure 11 shows two typical Test Track CTM range distributions. The range values are higher than the controlled laboratory study. Typically, range values above 0.50 were examined further. Examining a suspect range of data consisted of reviewing the nine replicate measurements and reviewing the 1/8th increment measurements provided in the CTM output file for each test. In most cases, no changes were made to the data. In a few cases, data were determined to be an outlier and were omitted.

The histogram of CTM ranges for all data sets through 2.6M ESALs is shown in Figure 12. The ASTM E2157 standard precision states that the CTM MPD has a standard deviation of 0.03 for eight replicate tests. This study only used three replicate measurements, so an acceptable precision standard deviation value would be higher than 0.03. Approximately 60% of the data sets had a range of MPD values less than 0.06 mm (+/- one standard deviation). Almost 80% of the data sets had MPD ranges less than 0.09 mm (+/- 1.5 standard deviations). A total of 35 sets of replicate results (20% of the total) had ranges exceeding 0.09 mm, and 66% of those 35 sets were located in sections W8A (granite) and W9C (silica). Overall, 75% of the CTM MPD results had COV values less than 5% based on range values.

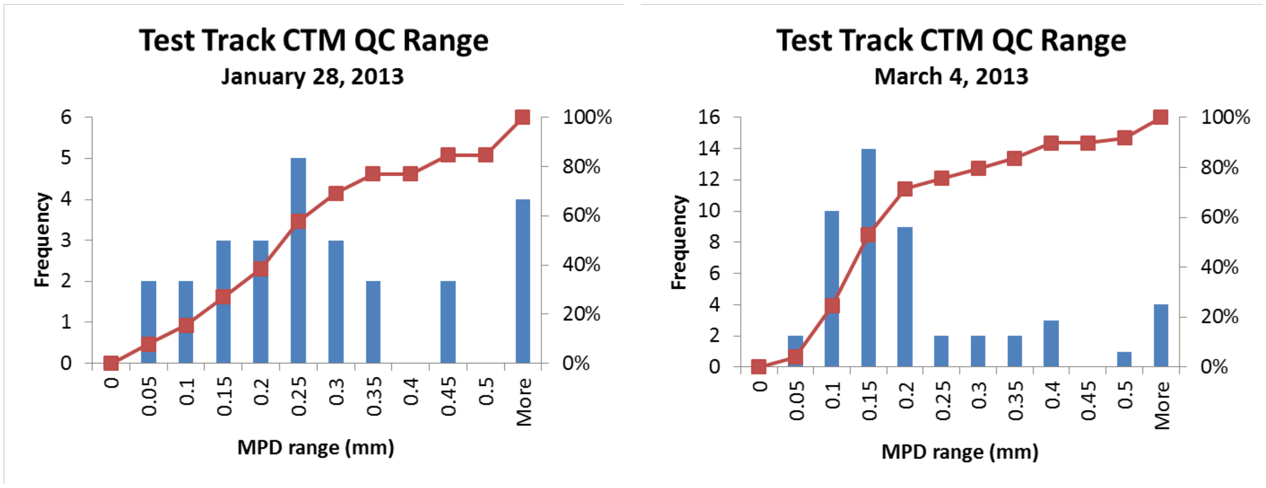


Figure 11 FIELD CTM QC Range Histograms

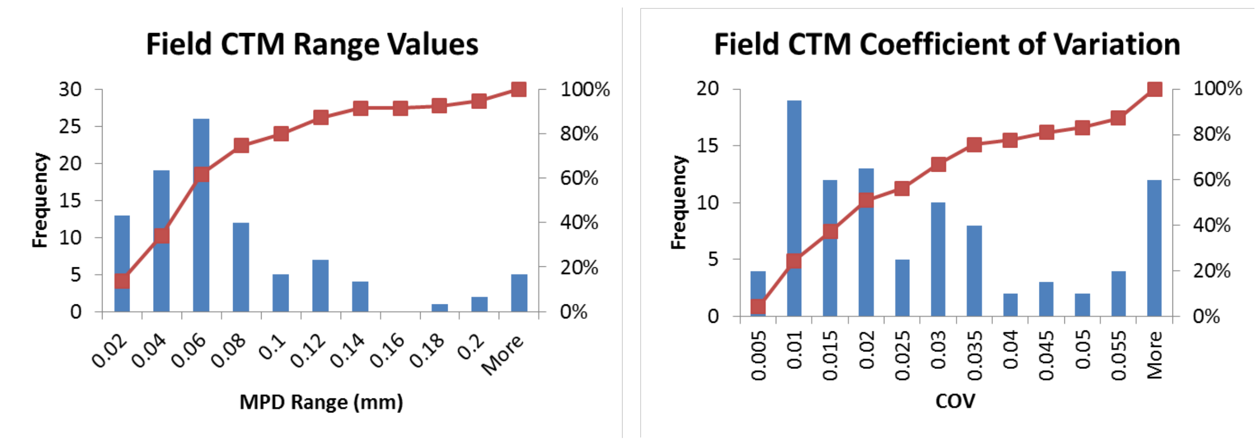


Figure 12 FIELD CTM Data Quality Control Summary

The quality control check process for DFT values was similar to checking CTM values, but separate range values were computed for multiple recorded test speeds for each replicate set of tests at each test location. For this data QC analysis, only the data from DFT measurement speeds of 20 km/h, 40 km/h, and 60 km/h (DFT(20), DFT(40), and DFT(60), respectively) were considered. DFT(0) and DFT(80) results are typically much more variable and therefore were not used. Measurements from three test speeds generated an acceptable number of three-point range values for the distribution analysis. This created sufficient data for both full Test Track data sets and exclusive HFST test sections data sets. Figure 13 shows two typical Test Track DFT range distributions. The range values are higher than the controlled laboratory study. Typically, range values above 0.10 were further examined. Examining a particular range consisted of reviewing the three replicate measurements for each measured speed. In most cases, no changes were made to the data. In some cases, a measured value was determined to be an outlier and was omitted.

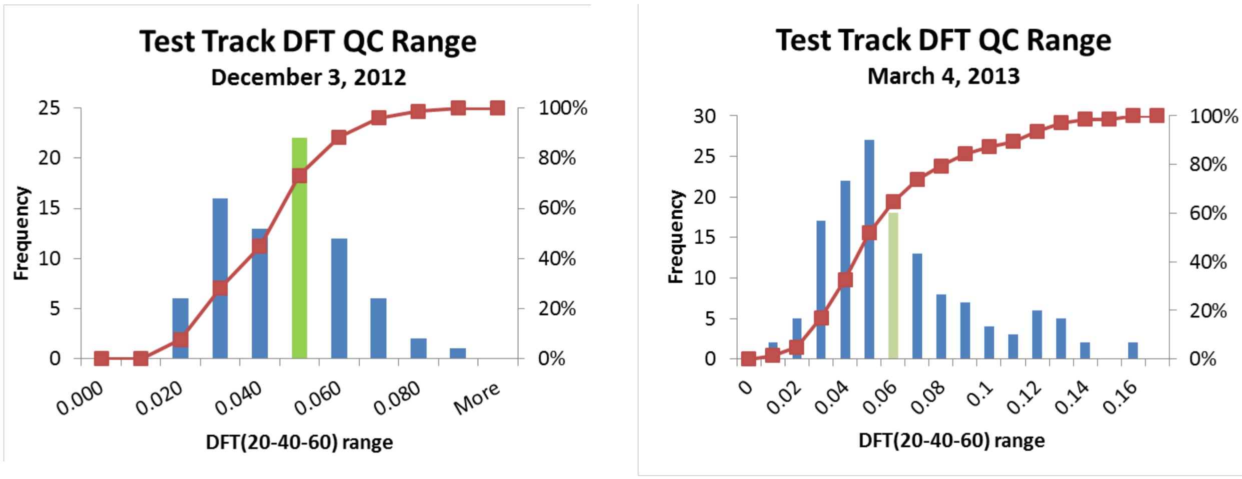


Figure 13 FIELD DFT QC Range Histograms

The histogram of all DFT ranges through 2.6M ESALs is shown in Figure 14. The data in the histogram represents the range of values for each set of three replicate results. The ASTM E1911 precision standard states that the DFT Fn has a standard deviation of 0.044 to 0.038 for eight replicate tests for the recorded friction at 30 km/h and 60 km/h. This study only used three replicate tests, so the acceptable precision standard deviation would be higher. Based on the range values presented in Figure 14, the quality of DFT data appeared to be acceptable. A total of 79% of the data sets had ranges of 0.04 or less and 99.9% of the remaining data sets had range values within plus/minus 1.5 standard deviations (0.12). Only one DFT Fn value exceeded 0.12. The coefficient of variation based on range values for the DFT measurements was less than 5% for 95% of the data sets.

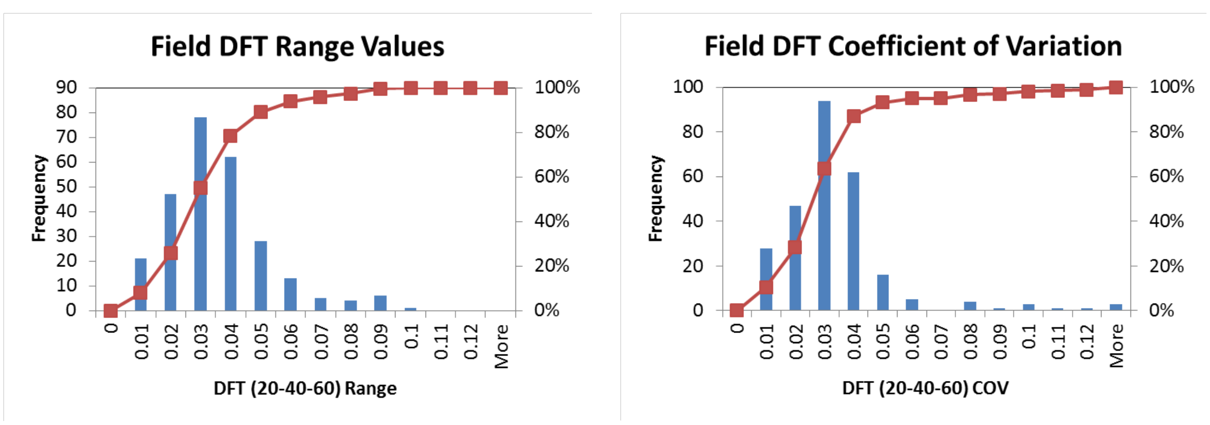


Figure 14 – FIELD DFT Data Quality Control Summary

The quality control check process for measurements from the locked wheel skid trailer was similar to checking DFT values. A range value was computed for each set of three-replicate SN40R tests. Skid trailer testing was only performed as complete Test Track data sets, so each test date generated over 40 three-point range values for the distribution analysis. Figure 15 shows two typical Test Track skid trailer range distributions. Generally, three-point range values above 5.0 were further examined. Examining a particular range consisted of reviewing the three replicate measurements. In most cases, no changes were made to the data. In some cases, a SN40R value was determined to be an outlier and was omitted.

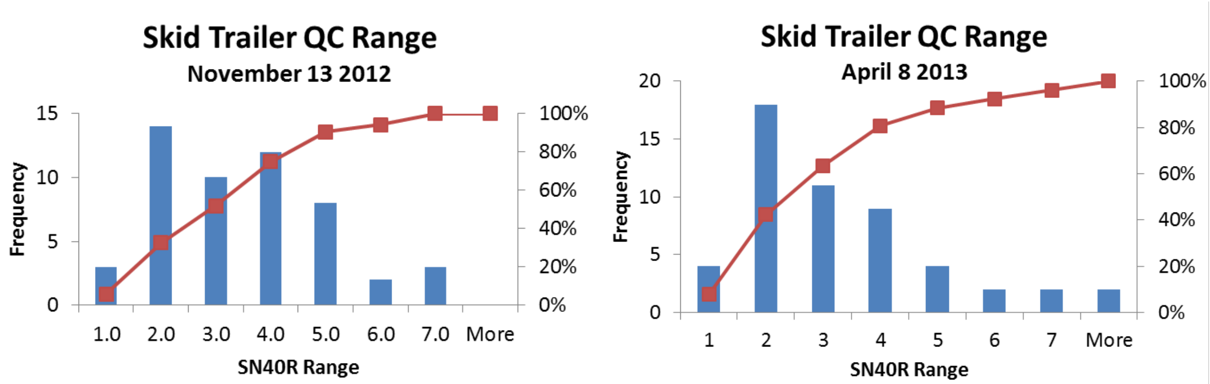


Figure 15 FIELD Skid Trailer QC Range Histograms

Data Analysis

FIELD compared the performance of the eight HFST aggregates based on three measured values: DFT friction, CTM texture, and skid trailer friction. Only DFT measurements at 40 km/hr, DFT(40), were used for the analysis of the DFT FIELD data. Table 4, presented above, summarizes the average values for each test date. The analysis examined the changes in HFST characteristics resulting from full-scale truck traffic conditioning. How each HFST surface changed with time was observed in addition to establishing a terminal value.

CTM Surface Texture

Figure 16 displays the surface texture (MPD) performance history for all eight HFST sections through 2.6M ESALs of truck traffic conditioning. Prior to traffic, the taconite and silica test sections measured the highest surface textures with MPD values of 1.85 mm. The bauxite test section had the least surface texture with an average MPD value of 1.41 mm. It must be noted that all of these macro-texture values are high compared to conventional dense-graded asphalt pavement surfaces which typically measure below 0.50 mm. All of the HFST materials, except basalt, showed lower MPD values after approximately one month of traffic, and in most cases values continued to gradually decrease through 2.6M ESALs of traffic conditioning.

The granite section showed a decrease in MPD after one month of traffic , a sharp increase in MPD after two months of traffic, and a sharp drop in MPD on the next testing date. This same behavior was also seen on a smaller scale in the DFT data and may be indicative of some type of surface anomaly in this test section. A visual examination of the surface showed some texture variation due to a segregated spread of coarser and finer aggregate particles. The three test locations are randomly selected each test date, so measured MPD would reflect differences in the surface texture along the length of the test section.

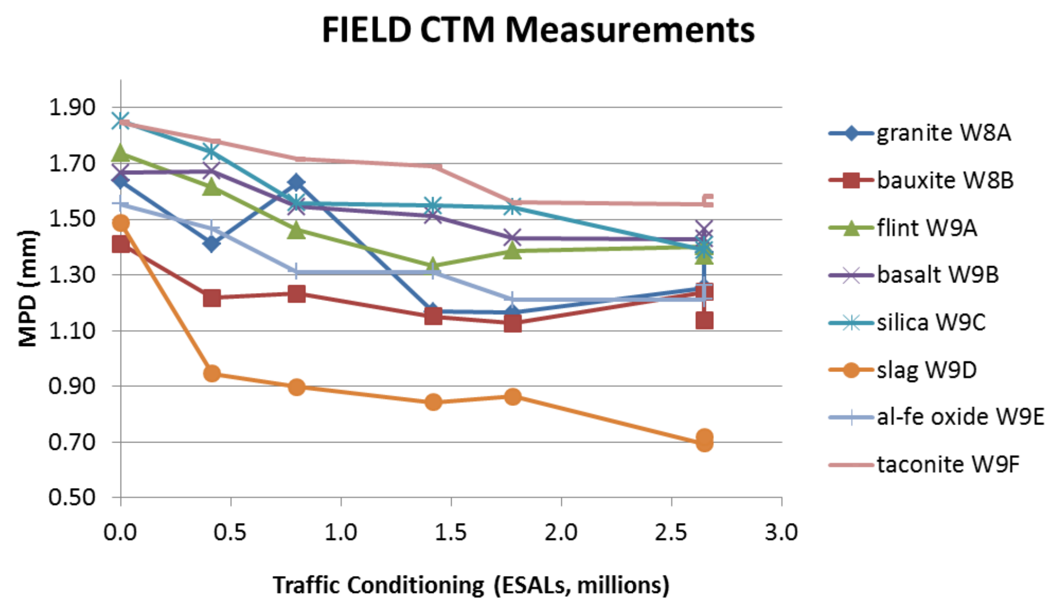


Figure 16 Left Wheel Path Surface Texture Measured by CTM

DFT Friction

Figure 17 displays the DFT(40) friction performance history for all eight test sections through 2.6M ESALs of traffic conditioning. Prior to traffic, the bauxite sub-section showed the highest surface friction with a DFT(40) Fn value of 0.92. Taconite had the second highest initial surface friction with a DFT(40) Fn value of 0.75, but was significantly lower than the bauxite. The slag test section had the lowest surface friction with a DFT(40) Fn value of 0.52. After one month of traffic, the wheel path Fn values for all of the HFST test sections had a general reduction of 0.15 in surface friction. The silica test section had the smallest initial reduction (0.03) while the alumina-ferrous oxide test section had the largest reduction (0.20). The most probable explanation for the reduction in measured friction within the first month is the traffic abrasion wearing down the sharp edges of the crushed faces on the surface of the aggregate particles.

With the exception of silica and alumina-ferrous oxide, most of the HFST test sections maintained their relative ranking of surface friction throughout the 2.6M ESALs conditioning period. Bauxite and taconite had the highest DFT(40) Fn values, and slag and granite had the lowest values over this period.

Approximately three months after traffic was stopped, another set of DFT tests were taken. This second set of results after 2.6M ESALs conditioning showed wheel path DFT(40) Fn values that were slightly higher compared to the previous test results for all of the test sections. This trend was most likely a reflection of changed testing conditions, not a change in the test surfaces, since traffic was stopped in October.

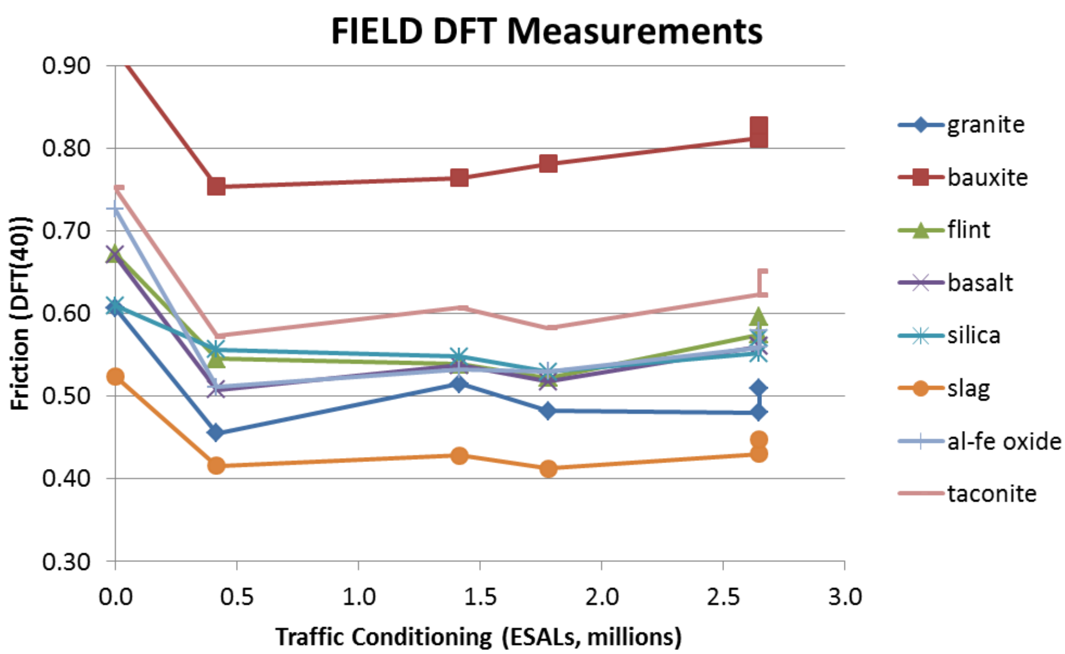


Figure 17 Left Wheel Path Friction Measured by DFT

Figure 18 displays friction performance history extended through 10M ESALs for the granite, bauxite, and flint test sections. The data used for this graph does not include the initial pre-traffic measurements. By omitting the pre-traffic measurement, the data represents the friction trend (as shown by the linear trend-line) over the course of traffic conditioning. There were large swings in the measured friction, but no data quality control indicators that showed the values are outliers. It is reasonable to conclude the large increases and decreases in measured DFT(40) values represent physical differences in HFST friction along each test section as well as testing variability. The linear trend lines represent a reasonable performance history for comparison between HFST test sections. Overall, the extended conditioning and testing of the three HFST test sections showed no change in the ranking of friction performance.

Most of the data sets displayed common increases or decreases over the same time periods. The decrease in measured friction at 6.5M ESALs occurred for both bauxite and granite. One probable factor in the test variation is the temperature at the time of testing. The DFT friction measurements consistently trended upward as the climate was getting colder and trended downward as the climate was getting warmer. This is not the only testing variable that may have contributed to the large swings, but certainly warrants additional study as part of a DFT ruggedness evaluation.

Skid Trailer Surface Friction

Figure 19 displays the skid trailer friction (SN40R) performance history for the granite, bauxite, and flint test sections through 10M ESALs of conditioning. As noted earlier in this report, skid trailer data was not reliable until 2.6M ESALs of traffic conditioning. In addition, two test results for bauxite (at 4.2M and 9.3M ESALs) were very low and omitted as outliers. Using the trend lines generated by the datasets, bauxite friction dropped from SN40R of 70 to 63 over the field conditioning period, flint dropped from 54 to 43, and granite dropped from 54 to 40. The results clearly show the bauxite HFST test section maintained higher friction levels. The flint and granite have similar friction performance histories, and the flint performed slightly better than the granite on most testing dates.

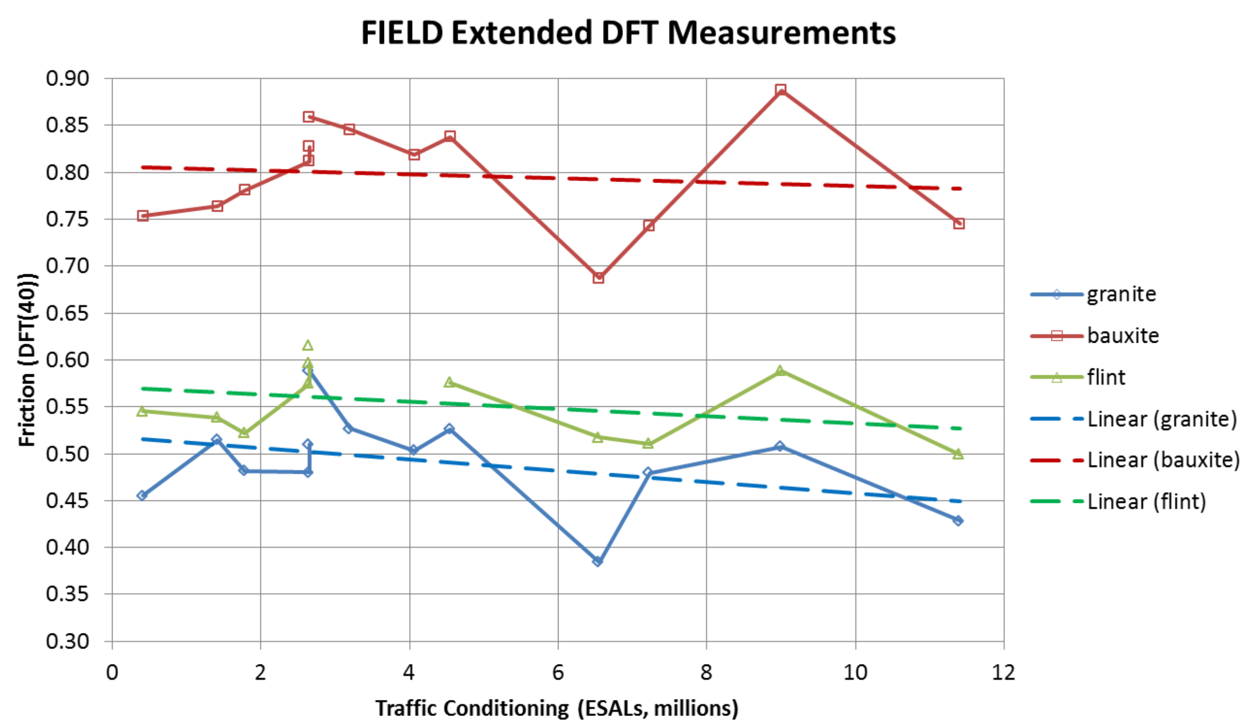


Figure 18 Left Wheel Path Friction by DFT After Extended Conditioning

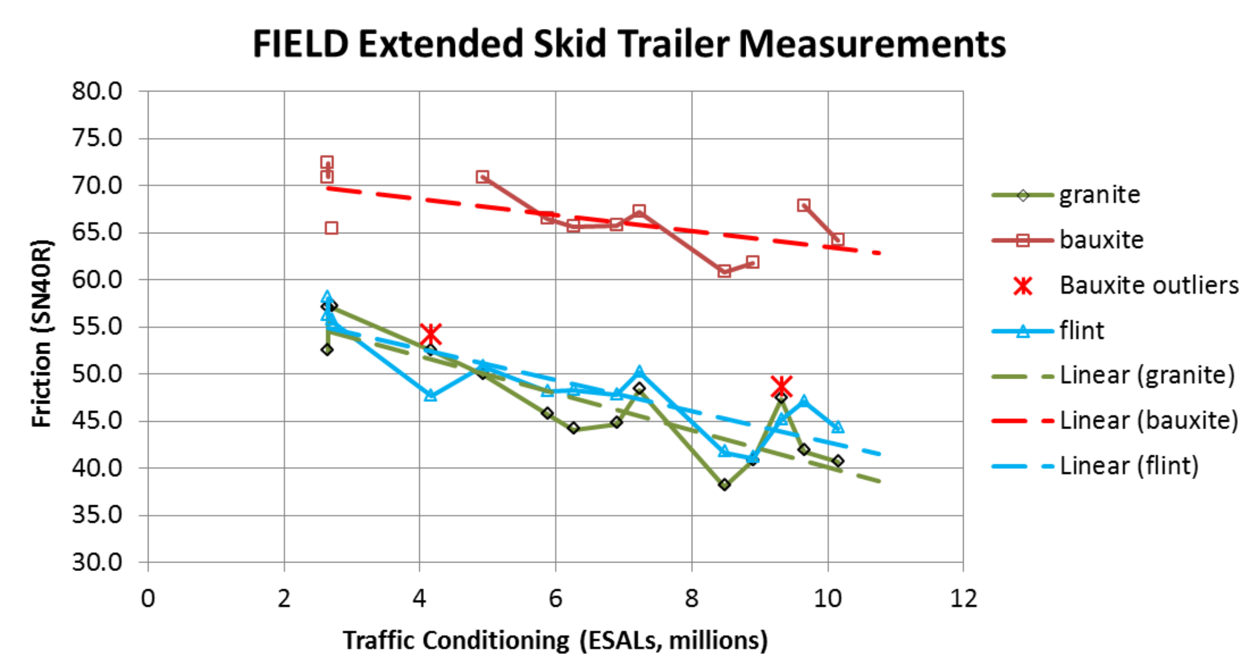


Figure 19 Left Wheel Path Skid Trailer Testing Summary

LAB-2 STUDY

LAB-2 was designed to address two objectives. The first objective was to determine if the size of the HFST aggregate particles influenced the measured friction. This part of the study used the NCAT TWPD, DFT, and CTM to measure change in macro-texture and friction resulting from rubber tire polishing. The second objective was to determine if other laboratory tests could be used to predict the HFST friction performance. Two testing processes were identified for this study. The commonly accepted aggregate friction test protocol using the British Pendulum (BP) (ASTM E303-93 *Measuring Surface Frictional Properties Using the British Pendulum Tester*) and British Wheel (ASTM D3319-11 *Accelerated Polishing of Aggregate Using the British Wheel*), and the second process involved the Aggregate Image Measurement System (AIMS) (ASTM TP81-12: *Determining Aggregate Shape Properties by Means of Digital Image Analysis)* combined with the Micro-Deval conditioner (ASTM D7428: *Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus)*.

<u>Sample Preparation</u>

Four HFST aggregate sources were selected for the second laboratory study. For clarity, these sources were called bauxite-2, slag-2, taconite-2 and flint-2 to distinguish them from the first laboratory study and FIELD. This unique source designation is important because the sources of these samples were not specifically tied to the sources used in the first lab study. The bauxite, taconite, and flint sources were similar to the LAB-1 material sources and the steel slag supplier was a different.

Sufficient quantity was delivered to the NCAT laboratory to screen an adequate amount of material to place HFST on three 20-inch by 20-inch test slabs from each aggregate source from particles retained on individual sieves. The screen stack used to split each sample included Nos. 4, 5, 6, 8, 12 and 16 sieves. All source gradations passed 100% of the particles through the No. 5 sieve. The No. 6 sieve retained 0 to 18%, the No. 8 sieve retained 19 to 55%, the No. 12 sieve retained 23 to 42%, and the No. 16 sieve retained 2 to 39%. Only 1 to 8% of the particles passed the No. 16 sieve.

The “as delivered” gradation of each source was not part of the LAB-2 scope. The proportion of particle sizes from each source was only quantified to determine how much material to screen and divide into individual particle sizes. No properly washed, split and screened gradation test was performed.

From the gradation split there was sufficient material to prepare three TWPD slabs from the No. 8 and No. 12 retained bins for all four sources. Additional slabs were prepared from No. 6 and No. 16 retained bins on a source by source basis. There was insufficient material to prepare replicate slabs for the No. 6 and No. 16 splits.

For this lab study, Kwik Bond Polymers PPC HFST Binder Resin was sent to the NCAT laboratory as three individual components. The manufacturer provided instructions for blending the components based on air temperature and desired curing time. All HFST were placed onto the TWPD slabs on the same day. Tape was placed on the vertical edge around the perimeter of each slab to contain the bonding agent. Small batches of bonding agent were proportioned, stirred, and placed on a small group of slabs. Immediately after the binder was placed, the aggregate was manually cast evenly across the surface of the slab. The slab surface was completely covered with HFST from edge to edge to avoid the surface offsets created on the first laboratory study. After the HFST cured, the surface of each slab was rubbed with a wooden board to dislodge loosely bound particles. The final step of slab preparation was to clean each surface with a stiff brush.

Three slabs were prepared for each source for the No. 8 and No. 12 particle sizes. Using the available material, one No. 6 slab was prepared for two aggregates and one No. 16 slab was prepared for three sources. Table 5 provides a summary of the slabs prepared for LAB-2.

Table 5 Summary of Slab Replicates

	Retained Sieve Size			
Aggregate Source	**No. 6**	**No. 8**	**No. 12**	**No. 16**
Bauxite-2		3 slabs	3 slabs	1 slab
Slag-2	1 slab	3 slabs	3 slabs	1 slab
Taconite-2		3 slabs	3 slabs	1 slab
Flint-2	1 slab	3 slabs	3 slabs	

A small amount of each source was used to prepare the testing coupons for the BP test. The standard aggregate size for this test is particles passing the 1/2-inch sieve and retained on the 3/8-inch sieve. This size particle is not available from standard HFST aggregate samples, as most HFST gradations pass all material through the No. 4 sieve. This study prepared blank BP coupons with the intent to adhere a layer of HFST aggregate to the surface of the coupon with a bonding agent. Two problems occurred during this attempted test modification. First, it was difficult to place a sufficient amount of bonding agent on a curved surface to adequately hold the No. 8 particles. Second, the polymer bonding agent would not adhere to the standard two-part epoxy blank coupon surface. After several attempts to resolve sample preparation issues, further attempts to use the BP test protocol were dropped.

The BP test protocol for friction aggregate is routinely specified for classifying aggregate sources. To measure the friction properties of aggregates used for HFST applications, the BP test protocol must provide an alternative sample preparation procedure. A test development study is needed to create and test aggregate samples that are smaller than the current 3/8-inch particle criteria. Compatibility between the BP molding epoxy and the aggregate bonding agent is needed.

A sample of each HFST source retained on the No. 8 sieve was used for the AIMS/Micro-Deval testing. No special sample preparation was needed for this test. Approximately 1000 grams of No. 8 sieve particles from each source was required for the Micro-Deval conditioning process. Further use of these four samples is described in the test procedure.

Test Protocol

A similar DFT/CTM testing and TWPD conditioning protocol described in LAB-1 was used for this second laboratory study. The issue with differential surface height between the DFT and the HFST was avoided by placing the HFST across the entire slab surface. Two of the three replicate slabs for the No. 8 and No. 12 aggregate size surfaces were selected for testing. Eight selected slabs (one replicate, two sizes, four sources) were tested as one group. The eight slabs were randomly re-sorted after each cycle of conditioning and testing. DFT rubber pads were replaced after every six drops. The testing sequence was repeated for the other group of eight slabs.

After testing was completed on the 16 slabs representing the No. 8 and No. 12 surfaces, the testing protocol was applied to the five slabs surfaced with No. 6 and No. 16 aggregates. The five slabs were treated as a group using similar random re-sorting after each cycle of conditioning and testing.

The AIMS/Micro-Deval testing protocol combines the aggregate angularity and surface texture measurements of the AIMS device with the conditioning and mass loss characteristics of the Micro-Deval test. The No. 8 retained particle size selected for this test procedure matched the software used by the AIMS device.

The testing protocol developed for this study using the AIMS/Micro-Deval processes was as follows:

1) Each aggregate sample was washed and oven dried prior to testing.
2) Approximately 500 grams of dry aggregate were obtained using proper aggregate splitting procedures to satisfy Micro-Deval test sample size specifications.
3) The 500 gr sample was further reduced to obtain three replicate AIMS samples. The AIMS device requires a significantly smaller sample size (150 minimum fine particle count, approximately 30 gr) than the Micro-Deval test. To obtain the AIMS samples, the 500 gr sample was first split in half to create two 250 gr samples. Using a random number generator, one of the two 250 gr samples was selected and further divided into eight smaller samples (approximately 30 gr each). Again, using a random number generator, three of the eight samples were selected for replicate image analysis. This process was completed for each of aggregate type prior to any AIMS testing.

For the purpose of this test protocol, a “run” refers to each time a 30 gr aggregate sample was analyzed in the AIMS device (three runs for each aggregate type for each analysis). A ”cycle” refers to the series of events that include conditioning a 500gr sample in the Micro-Deval, measuring the mass-loss of the large sample, drying the sample, splitting the sample into eight 30 gr samples, and analysis of three small samples by the AIMS device.

4) Three replicate 30 gr samples of each aggregate were measured in the AIMS and checked against the precision statement in ASTM TP81-12: *Determining Aggregate Shape Properties by Means of Digital Image Analysis.* Each 30 gr run measured over 200 individual particles.
5) Once analysis in the AIMS was complete and checked for repeatability, the samples were recombined to make up the overall 500 gram sample. The combined sample was placed in the Micro-Deval container for conditioning.
6) ASTM D7428: *Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus* was followed to carry out aggregate conditioning for 25 minutes in the Micro-Deval.
7) The combined 500 gr sample was removed from the Micro-Deval, washed over the No. 30 sieve, placed in an oven to dry, and weighed for total mass loss.
8) Steps 3 and 4 were repeated to complete one cycle of conditioning and testing.
9) Steps 5, 6 and 7 were repeated to complete the second cycle of testing.
10) The results were recorded and analyzed for aggregate angularity, aggregate shape, and mass loss after 0, 25, and 50 minutes of conditioning.

Because the samples for this study were single sieve size (not a blended gradation sample as specified in ASTM D7428), a few adjustments were made to the procedure to meet research needs.

A. The initial 500-gram sample of fine aggregate, 0.75 liters of water, and 1250 +/- 5 gr of stainless steel balls remained consistent throughout testing.
B. Material passing the No. 30 sieve was considered lost material as opposed to material passing the No. 200 sieve, as specified in ASTM D7428.
C. The aggregates were conditioned in the Micro-Deval for two 25-minute cycles (a total of 50 minutes). ASTM D7428 specifies that fine aggregate samples should be conditioned in the Micro-Deval for a total of 15 minutes. The aggregates for this study were characterized as having high friction properties, so a longer conditioning time was more desirable in order to ensure the aggregates would be noticeably degraded in the Micro-Deval.

Test Quality Control

During the two 70,000 cycle TWPD conditioning periods on the test slabs, differing degrees of aggregate loss from the surface of the slab were observed. As a point of reference, there was no aggregate loss observed during the first laboratory study. Figure 20 provides a subjective observation of the amount of aggregate loss for each slab. Figures 21 and 22 show two photos of slab surfaces with different amounts of aggregate loss. The slabs with flint (chat) aggregate had major loss and the taconite slabs had no loss. The data analysis section will examine the impact of the aggregate loss on measured surface texture and friction properties.

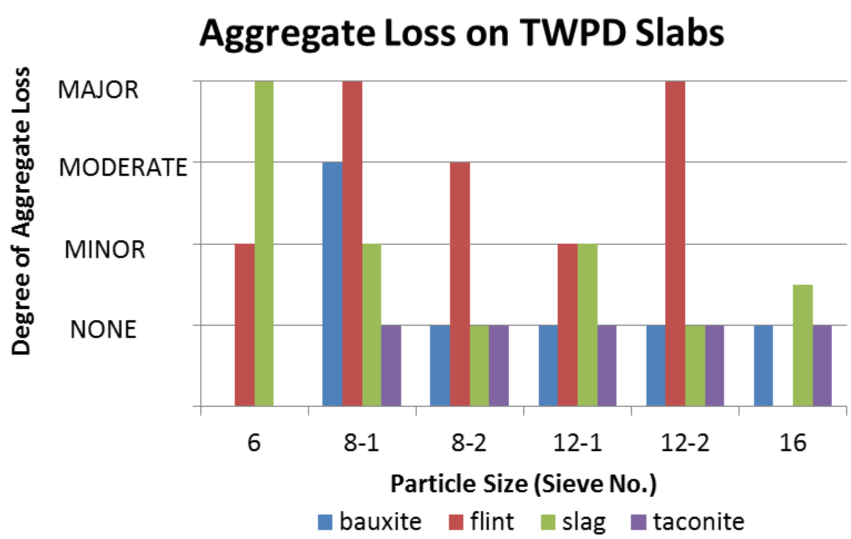


Figure 20 Observed Aggregate Loss on Slabs

Figure 21 Photo of Severe Aggregate Loss

Figure 22 Photo of Minor Aggregate Loss

The DFT and CTM testing consisted of 48 sets of replicate measurements for the primary particle sizes (three cycles, two slabs, two sizes, four aggregates) plus an additional ten sets for the expanded particle size range (two cycles, one slab, five size/aggregate). The quality control evaluation for DFT data used the range values for all five measurement speeds 0, 20, 40, 60, and 80 km/h. The histograms for the three-replicate test ranges are shown in Figure 23 for the No. 8 and No. 12 particle sizes and the No. 6 and No. 16 sizes. As noted earlier in the report, the precision for the DFT range on three replicates is above 0.12. The histogram cumulative curves show over 90% of the range values fall below 0.12. The variation displayed in each histogram is slightly higher than in LAB-1 because 40% of the range values are for 0 and 80 km/h measurements, which have higher variation. The data set of DFT(40) values used in the analysis is within the precision criteria.

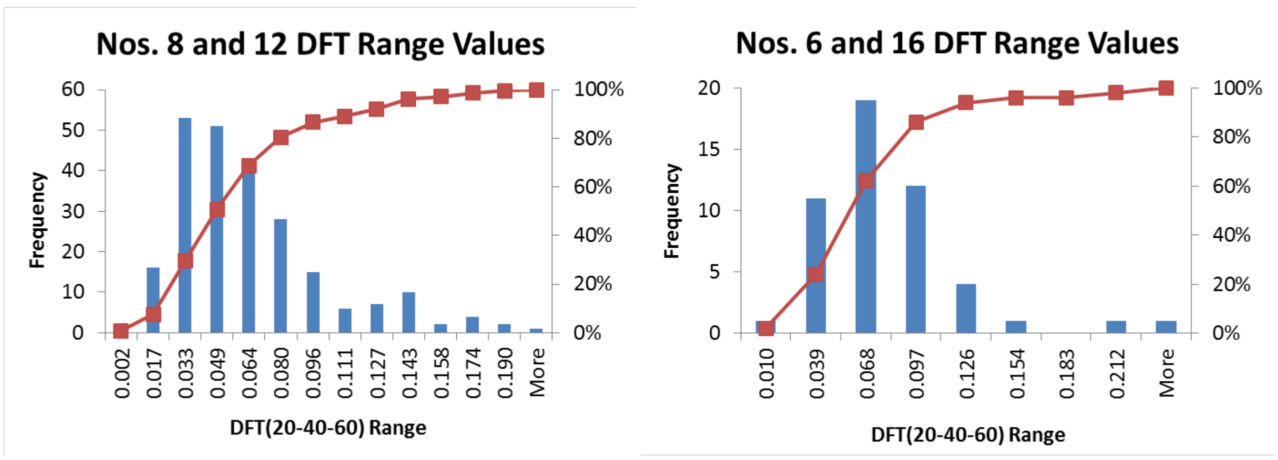


Figure 23 LAB-2 DFT QC Range Histograms

The quality control evaluation for CTM data followed a similar process and the results are comparable to LAB-1. The data sets contain five replicate measurements and the allowable range should be less than 0.117. In Figure 24, approximately 72% of the range values for the No. 8 and No. 12 slabs are below the ASTM allowable value and 95% of the range values were below two standard deviations from the mean. Two range values exceeded three standard deviations from the mean and were addressed as outliers. There were only 15 range values for the five No. 6 and No. 16 slabs, so the QC analysis used the statistics of the large set of CTM ranges. Over 85% of the range values met the precision criteria and all 15 ranges were below the two standard deviation limit.

The AIMS/Micro-Deval testing protocol used the precision criteria established for the AIMS measurements for the quality control analysis. Each AIMS test for No. 8 sieve particles generates over 600 individual measurements to create a distribution curve. A mean and standard deviation are calculated for each set of measurements. Individual measurements that are outside of three standard deviations are automatically removed as outliers. Three replicate tests were performed to create three replicate sets of measurements. The three replicate data tests are compared statistically. Acceptable test precision for particle angularity requires the mean of each replicate data set to be within 2.9% of the mean of the three replicate means. Acceptable test precision for particle Form2D requires the mean of each replicate data set to be within 2.7% of the mean of the three replicate means. All 72 tests (two tests, three replicates, three conditioning periods, four aggregates) met the quality control criteria. Figure 25 displays the coefficient of variation based on the three individual replicate standard deviations and the overall three-replicate mean. The COV values all fall below 2%.

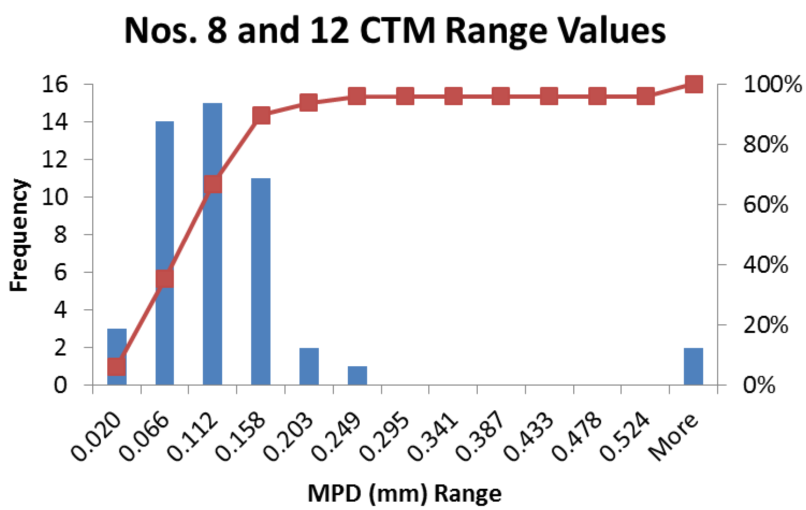


Figure 24 LAB-2 CTM QC Range Histogram

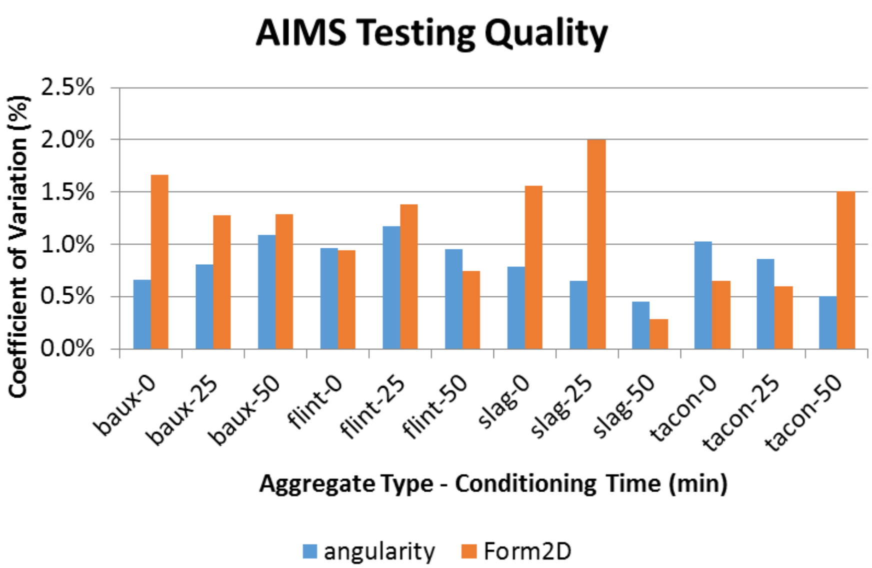


Figure 25 AIMS Testing Quality Control Summary

Data Analysis

The primary purpose of LAB-2 was to determine the impact of particle size on surface friction characteristics. The NCAT TWPD conditioned the surfaces and the DFT and CTM measured the texture and friction. The second purpose of the study was to examine other lab testing protocols for aggregate quality as a ranking tool for HFST friction performance. The Micro-Deval device conditioned the aggregate and the AIMS measured particle angularity and shape. The study was not able to develop an acceptable sample preparation procedure for the BP test.

CTM and DFT Test Results

The surface texture (MPD) data measured with the CTM showed some texture reduction between the initial values and the measurements after 70K conditioning cycles, but showed very little change between 70K and 140K cycles. These observations were consistent with expected surface response and the results of LAB-1. During the first 70K cycles of conditioning, aggregate particles that are loosely bound and particles with angular, but weak, exposed corners are worn by the mechanical scrubbing force of the TWPD tires. Between 70K and 140K cycles in the TWPD, the HFST surface is stable and the polish resistant aggregate does not change. Figure 26 displays the results for one aggregate type and a complete set of graphs are included in Appendix B.

The analysis further shows the results from the two replicate slabs prepared for the No. 8 and No. 12 aggregate sizes were very similar. Based on the consistency of the results, the four measured MPD values for both slabs at 70K and 140K conditioning cycles were averaged to define the texture of each aggregate-particle size combination. Figure 27 presents a summary of the texture measurements after conditioning. As expected, the results show that surface texture decreased as particle size decreased.

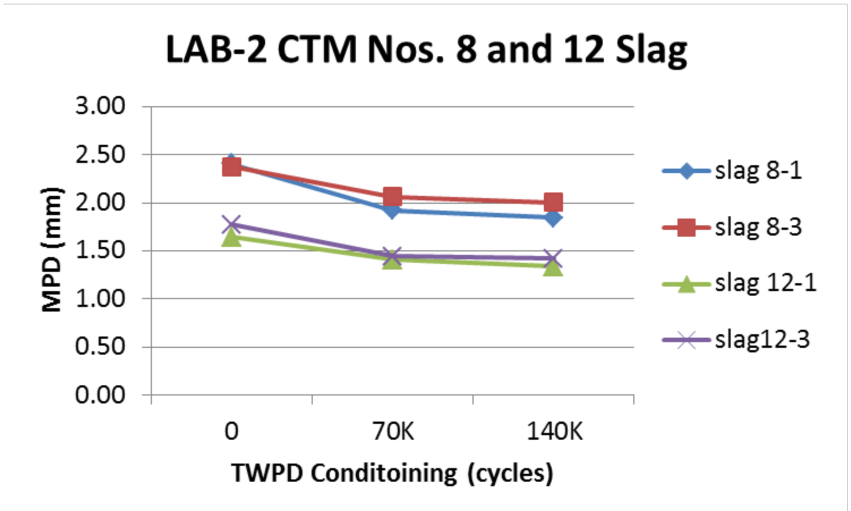


Figure 26 Typical Surface Texture Results for One Aggregate

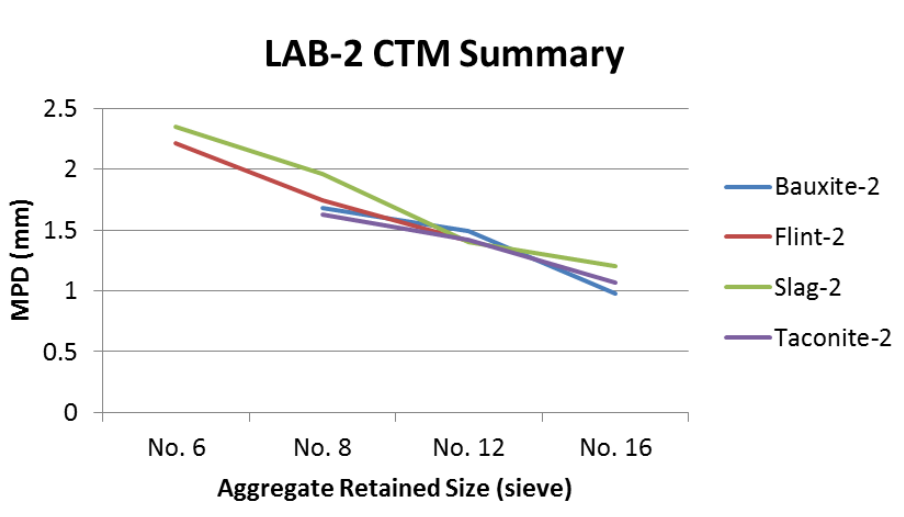


Figure 27 Summary of LAB-2 CTM Surface Texture Measurements

The results of the DFT friction measurements were similar to the surface texture results. The results for one pair of slabs in Figure 28 shows very high friction values before TWPD conditioning and no change in friction between measurements at 70K and 140K cycles. The HFST surface before conditioning displayed very high friction due to the crushed particle angularity and aggregate surface micro-texture. During the first conditioning period, the angularity and micro-texture were changed by the TWPD tire abrasion. After additional conditioning the friction results indicate that the aggregate resisted additional polishing. The graph displays the results for three DFT measurements speeds: 20, 40, and 60 km/h. Based on the consistency of the results at 70K and 140K cycles, the four DFT measurements for both slabs at 70K and 140K cycles were averaged for each test speed. A complete set of graphs is included in Appendix B.

The reduction in friction during the first conditioning period from 0 to 70,000 cycles is shown as a linear change in Figure 28. It is not possible to interpolate the shape of the actual decrease using just three measurements. Based on past laboratory friction studies, it is probable that the decrease occurs within the first 20K to 40K cycles.

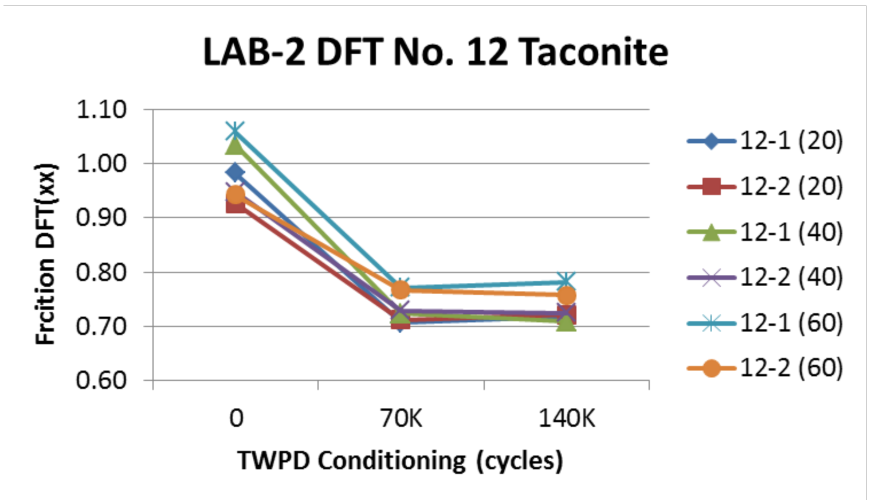


Figure 28 Typical DFT Friction Results for One Aggregate and Particle Size

Figure 29 shows a summary of the averaged terminal friction values for the four aggregates at No. 8 and No. 12 particles sizes. The bar chart displays an increase in friction as DFT measurement speed increased for flint and taconite, but no influence of speed on the bauxite and slag results. Later in the analysis, this study looks at the influence of particle shape and angularity as possible explanations for this difference. Consistent with previous studies, the DFT(40) values were used for additional analysis. A second observation from Figure 29 is the similarity between the friction results for No. 8 and No. 12 particles. For each aggregate type, there is no consistent trend between the friction results based on particles size. For bauxite, flint, and taconite there is no difference relative to particle size. The slabs surfaced with slag HFST aggregate showed a decrease in friction as particle size decreased.

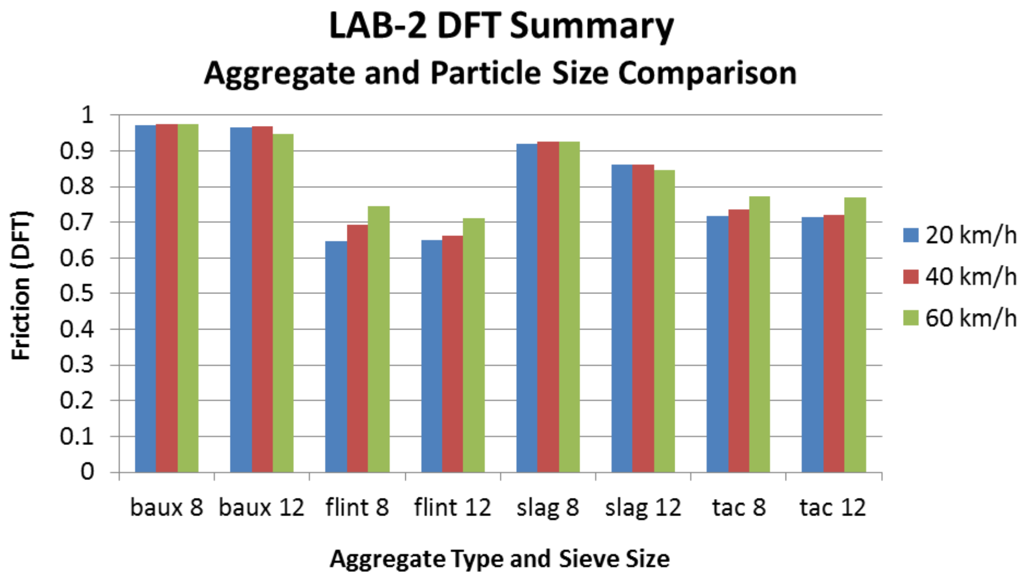


Figure 29 Summary of Terminal DFT Friction Results at Three Measurements Speeds

Figure 30 presents a summary of the friction results for all four aggregates at four particle sizes. Each data point at No. 8 and No. 12 represents the average of four measurements taken at 40 km/h after conditioning. The average at No. 6 and No. 16 are based on two measurements on one slab. Particle size does not appear to have a consistent effect on surface friction. Both the surfaces with large particles (No. 6) and the surfaces with small particles (No. 16) trend lower. Displaying the data using another perspective, Figure 31 shows the friction plotted in relation to the surface texture. Using the measured surface texture is a more precise method of expressing the influence of particle size than a retained sieve size. The graph shows a general increase in friction for each aggregate type as the surface texture increases to a MPD of 2.0 mm. The friction decreases when the MPD is greater than 2.0 mm. Aggregate loss during TWPD conditioning may be an influence on the friction values where the surface texture exceeds 2.0 mm. Only one slab was tested at No. 6 particle size for two of the aggregate sources, so there was insufficient data to evaluate the impact of aggregate loss on No. 6 aggregate during the test.

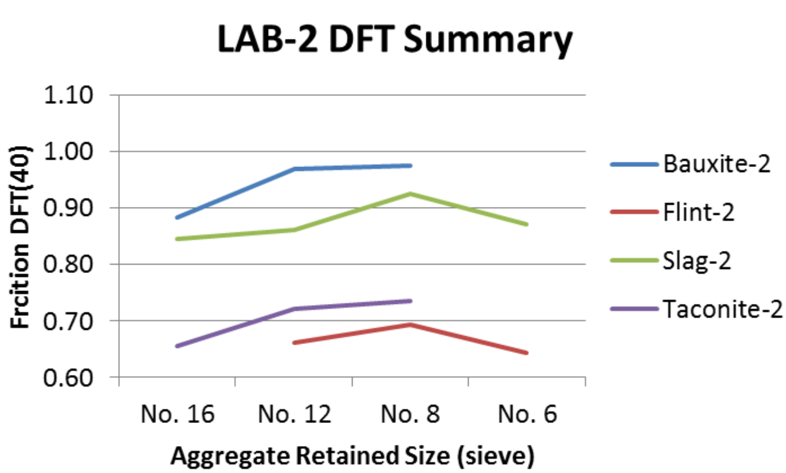


Figure 30 Summary of Terminal DFT Friction Relative to Particle Size

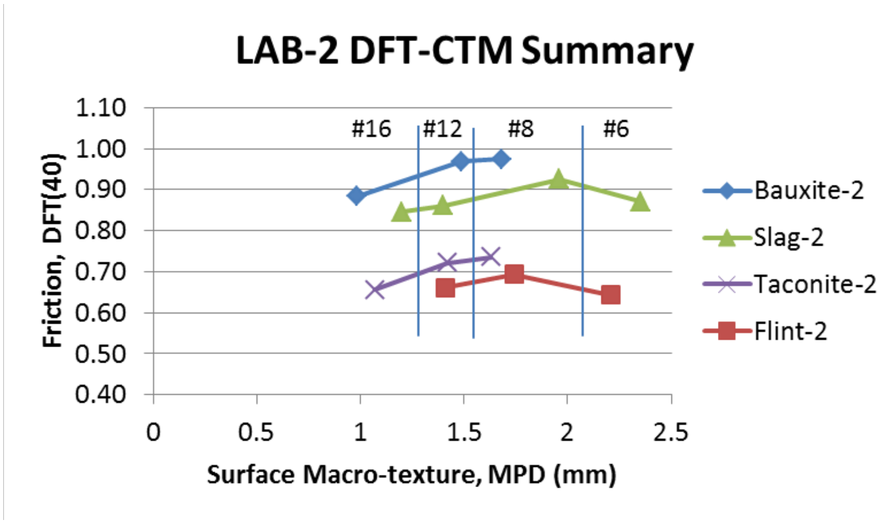


Figure 31 Summary of Terminal DFT Friction Relative to CTM Surface Texture

Did the aggregate loss on certain slabs impact the results? Several factors were probable causes for the aggregate loss in LAB-2. One key factor was the second laboratory study separated the aggregate particles into individual sizes across four sieves. With all of the particles similar in size, there was more void space between the aggregates that needed to be filled with bonding agent to achieve the good depth of aggregate bonding. A second factor was the process for preparing the test slabs used a uniform amount of bonding agent for each slab. The test protocol for slab preparation kept the volume of binder applied to each slab constant and did not take into account the differences in particle size. It was observed that the depth of bonding increased as the size of the particle became smaller. Standard HFST gradations include particles across three to four sieve sizes, which improves the ability to achieve good bond between the bonding agent and the particles. Smaller particles occupy a portion of the void space between the larger particles, which in-turn displaces the bonding agent higher around the larger particles.

The CTM and DFT measurements did not consistently indicate that the loss of aggregate had an impact. Two slabs were tested for each aggregate type for particles retained on the No. 8 and No. 12 sieves. The measured DFT friction after 140K TWPD conditioning was 0.05 to 0.08 lower for the second flint No. 12 slab, first bauxite No. 8, first flint No. 8, first slag No. 8 and first slag No. 12. These slabs had observed aggregate loss, but the measured friction differences also occurred on the same slabs before the TWPD abraded the aggregate off the slab. Similarly, the CTM measurements did not show differences. The bauxite No. 8 measurements were very similar, the flint No. 8 showed mixed results between 70,000 and 140,000, the second flint No. 12 final MPD measurements were lower (but the initial values were also lower), the first slag No. 8 showed a 0.2 mm reduction, and the slag No. 12 results were similar.

Using the DFT and CTM results of LAB-2, there was a decrease of measured friction as the surface texture decreased from a MPD of 2.0 mm to 1.0 mm. This is comparable to a common HFST blend dominated with No. 8 particles to a fine blend dominated by No. 16 particles. This reduction of surface texture caused a loss of up to 0.10 friction using DFT(40) values. The surface texture measurements from LAB-1 generally ranged from 1.65 mm to 1.35. The lowest LAB-1 surface texture was 1.15 for the first slag source. If the slag particle blend was improved to a MPD of 1.65, the friction may increase from 0.50 to 0.55 DFT(40).

AIMS/Micro-Deval Test Results

The objective of this portion of LAB-2 was to determine if another laboratory protocol could properly rank HFST aggregates as a function of friction performance. The Micro-Deval conditioned the aggregates for 50 minutes using a tumbling abrasion action and the samples were measured for weight loss resulting from the particle degradation. The AIMS device generated objective measurements of individual particle shape and angularity before conditioning, after 25 minutes of Micro-Deval conditioning, and after an additional 25 minutes of conditioning.

The Micro-Deval test is designed to quantify aggregate abrasion and durability (ASTM D7428: *Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus)*. This study looked at the ability of Micro-Deval conditioning to rank differences in high quality friction aggregates. Although the standard Micro-Deval conditioning period is 15 minutes, LAB-2 extended the conditioning to 50 minutes with the intent of reaching a terminal mass loss condition. Figure 32 shows the results of the mass loss measurements. The results show differences between the HFST aggregates and show that the aggregates continued to lose mass for up to 50 minutes of conditioning. The rate of mass loss did not change for three aggregates, but did start to diminish for slag. For this study, the mass loss at 50 minutes will be used for aggregate ranking, but the values do not represent a terminal abrasion loss state.

The Micro-Deval test ranks bauxite as the best performer and taconite as the lowest performer based on aggregate mass loss. To keep the results in perspective, most aggregates commonly used for asphalt mixtures would measure more than 20% mass loss after 30 minutes of conditioning. Figure 33 displays the Micro-Deval mass loss results with LAB-2 DFT friction results. The aggregates are listed in descending order of LAB-2 terminal DFT friction values. For the first three aggregates, the mass loss values increase appropriately, but the lower mass loss value for flint does not correlate with the friction ranking. Mass loss appears to provide a reasonable ranking of HFST aggregates but there is the potential for a false-positive result, like flint.

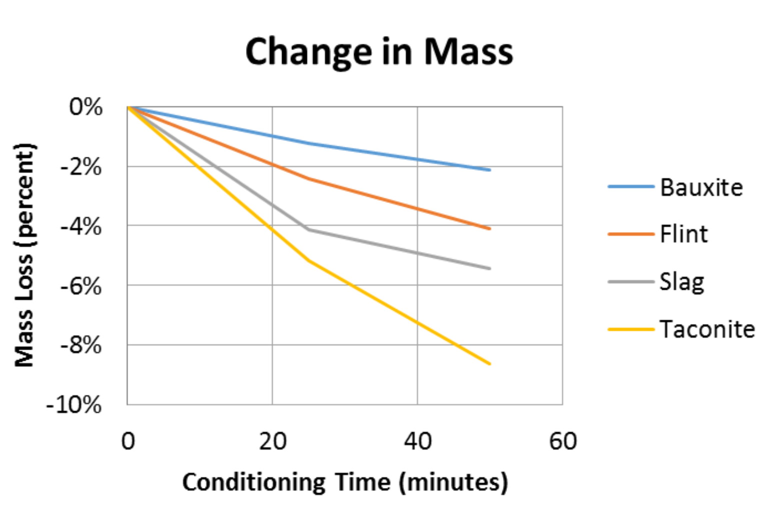


Figure 32 Micro-Deval Mass Loss Test Results

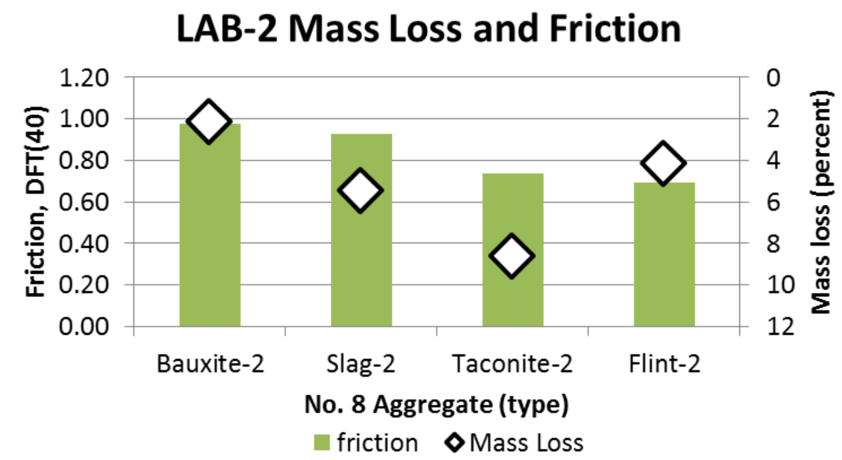


Figure 33 Comparison of DFT Friction and Micro-Deval Mass Loss

The AIMS device captures particle shape, angularity, and surface texture for coarse aggregate samples, but only captures shape and angularity for fine aggregate samples (AASHTO PP64-10: *Determining Aggregate Source Shape Values from Digital Image Analysis Shape Properties* and AASHTO TP81-10: *Determining Aggregate Shape Properties by Means of Digital Image Analysis*). The No. 8 size particles are the largest dominant aggregate size in HFST aggregate gradations and are classified as fine aggregate for AIMS testing. Therefore, this study was limited to evaluating the shape and angularity of four aggregate sources.

The AIMS device quantifies the shape of a particle on a range of zero (0) for a sphere to twenty (20) for extremely elongated shapes. From visual observation, the bauxite and taconite appeared to be more cubical and the flint and slag were more elongated. The AIMS measurements quantified all four aggregates in a narrow range of 6 to 8, as shown in Figure 34. Three of the aggregate sources showed very little change in particle shape after 50 minutes of Micro-Deval conditioning. Taconite had a slight shape change during the first 25 minute conditioning period but very little change after the second conditioning period. The results of AIMS shape measurements did not correlate to HFST friction rankings and were not given further consideration in the analysis.

The AIMS device measures the angularity of a minimum of 200 fine aggregate particles for each test. The individual particle angularity values are reported as a cumulative distribution curve. Figure 35 shows the terminal angularity for each HFST aggregate source based on the average of three samples. The shape of the distribution curves became approximately 10% steeper as the aggregates changed after Micro-Deval conditioning. The results show particle angularity of bauxite and taconite are very similar. The flint sample had a higher mean angularity and a very similar distribution. The slag aggregate had the highest angularity and the distribution of particle angularity was broader. The AIMS test procedure qualifies values below 3300 as low angularity and values above 6600 as high angularity.

The angularity values after 50 minutes of Micro-Deval conditioning were selected for comparison with other test results. This decision was based on observations that the computed angularity mean and accumulative distribution changed very little after conditioning. Figure 36 shows the mean angularity for each aggregate source during the process of conditioning. The only notable change was a slight reduction in angularity for the taconite aggregate during the first 25 minute conditioning period. This observed change matched the noted change in particle shape (Figure 34).

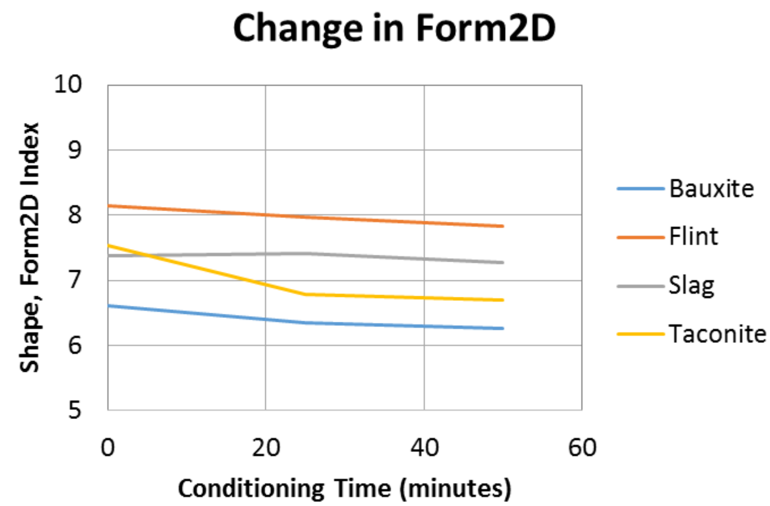


Figure 34 AIMS Shape (Form2D) Results

Figure 37 compares the terminal DFT(40) friction values to the terminal angularity values. The friction values were used to list the aggregates in descending rank from high to low. The AIMS angularity values are super-imposed over the friction bar graph. The anticipated trend would be that higher angularity achieves higher friction, but LAB-2 results show no correlation between particle angularity and DFT friction.

The earlier LAB-2 DFT summary in Figure 29 noted some influence of DFT measurement speed for flint and taconite but no influence for bauxite and slag. Comparing the results for Micro-Deval mass loss, AIMS shape, and AIMS angularity to the DFT results showed no correlation. None of the three sets of test results paired with all the measured DFT data.

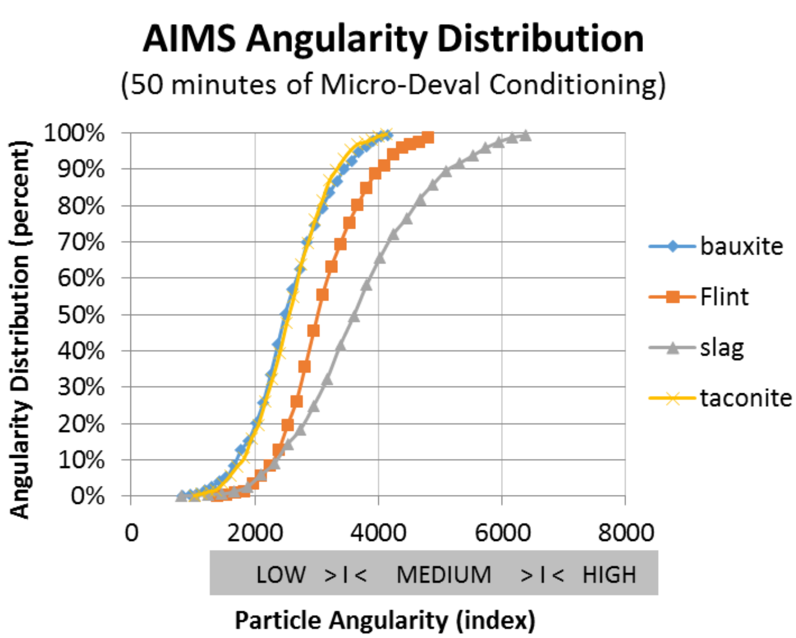


Figure 35 AIMS Particle Angularity Distribution at Terminal Conditioning

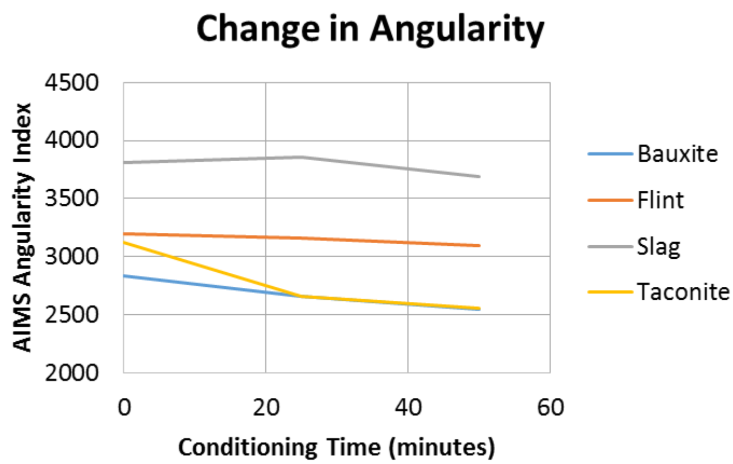


Figure 36 – AIMS Mean Angularity Results

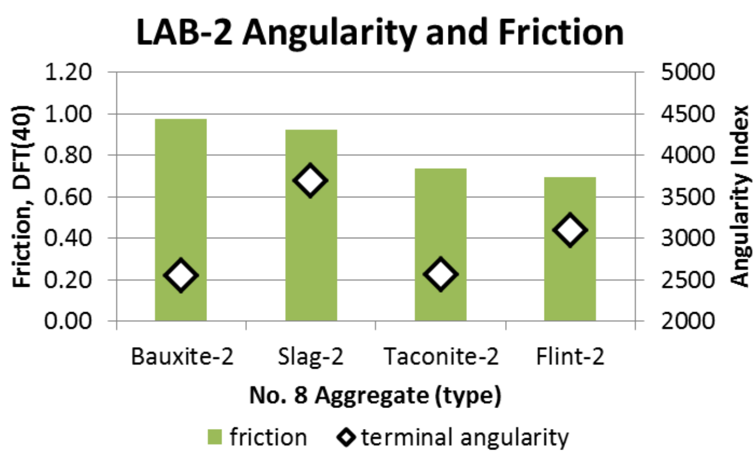


Figure 37 Comparison of DFT Friction and AIMS Angularity

CORRELATION ANALYSIS

This study was divided into three primary phases: first laboratory phase (LAB-1), field phase (FIELD), and second laboratory phase (LAB-2). Table 6 is a summary of the materials and tests associated with each phase. The BP test was a part of LAB-2, but the test protocol could not be modified to accommodate the size of HFST aggregate particles.

Table 6 Summary of Tests Performed

MATERIAL	Field ID	Sample ID	DFT	CTM	SKID	BP	AIMS
LAB-1 Study							
Granite	W8 A	A	X	X			
Bauxite-1	W8 B	B	X	X			
Flint-1	W9 A	C	X	X			
Basalt	W9 B	D	X	X			
Silica	W9 C	E	X	X			
Slag-1	W9 D	F	X	X			
Emery	W9 E	G	X	X			
Taconite-1	W9 F	H	X	X			
FIELD Study							
Granite	W8 A	A	X	X	X		
Bauxite	W8 B	B	X	X	X		
Flint	W9 A	C	X	X	X		
Basalt	W9 B	D	X	X			
Silica	W9 C	E	X	X			
Slag	W9 D	F	X	X			
Emery	W9 E	G	X	X			
Taconite	W9 F	H	X	X			
LAB-2 Study							
Bauxite-2		B2	X	X		no test	X
Flint-2		C2	X	X		no test	X
Slag-2		F2	X	X		no test	X
Taconite-2		H2	X	X		no test	X

Table 7 is a summary of the results of the testing. The table is divided to three parts. The first five rows are the results from field measurements. The next ten rows are laboratory measurements using the DFT and CTM. The last four rows are results from AIMS/Micro-Deval testing. The materials are listed in the order they were placed on the NCAT Test Track. The first seven columns provide a brief description of the testing performed for the values in the columns to the right. It is important to recognize that all of the reported values do not represent the same testing conditions.

From this set of test results a number of correlations between results were examined. Each comparison is discussed below.

Table 7 Summary of Test Results

Study Phase	Test Description	Test Method	Conditioning Period	Listed Value	Sample Gradation	Measurement Unit	Granite W8 A	Bauxite-1/2 W8 B	Flint-1/2 W9 A	Basalt W9 B	Silica W9 C	Slag-1/2 W9 D	Emery W9 E	Taconite-1/2 W9 F
FIELD	friction	DFT	2.6M ESALs	lin. trend	blend	DFT(40)	0.51	0.80	0.56	-	-	-	-	-
	friction	DFT		5 pt avg	blend	DFT(40)	0.49	0.79	0.56	0.54	0.55	0.43	0.54	0.61
	texture	CTM		4 pt avg	blend	MPD(mm)	1.24	1.16	1.37	1.46	1.47	0.78	1.25	1.60
	friction	SKID	10M ESALs	lin. trend	blend	SN40R	40	64	43	-	-	-	-	-
	friction	DFT		lin. trend	blend	DFT(40)	0.46	0.78	0.53	-	-	-	-	-
LAB 1	friction	DFT	140K TWPD	avg 70-140	Blend	DFT(40)	0.58	0.84	0.62	0.66	0.51	0.49	0.64	0.70
LAB 2	friction				No 6	DFT(40)	-	-	0.64	-	-	0.87	-	-
	friction				No 8	DFT(40)	-	0.97	0.69	-	-	0.93	-	0.74
	friction				No 12	DFT(40)	-	0.97	0.66	-	-	0.86	-	0.72
	friction				No 16	DFT(40)	-	0.88	-	-	-	0.85	-	0.66
LAB 1	texture	CTM	140K TWPD	avg 70-140	Blend	MPD (mm)	1.47	1.40	1.56	1.55	1.66	1.15	1.37	1.57
LAB 2	texture				No 6	MPD (mm)	-	-	2.21	-	-	2.35	-	-
	texture				No 8	MPD (mm)	-	1.68	1.74	-	-	1.96	-	1.63
	texture				No 12	MPD (mm)	-	1.49	1.41	-	-	1.40	-	1.42
	texture				No 16	MPD (mm)	-	0.98	-	-	-	1.20	-	1.07
LAB 2	mass loss	Mic Dev	50 min. M-D	terminal	No 8	percent	-	2.1	4.1	-	-	5.4	-	8.6
	angularity	AImS			No 8	(mean)	-	2546	3096	-	-	3690	-	2559
	angularity				No 8	(std dev)	-	654	667	-	-	1056	-	590
	shape				No 8	(mean)	-	6.3	7.8	-	-	7.3	-	6.7

Cells with a (-) represent no testing was performed

LAB-1 and FIELD Comparisons

The HFST materials tested in LAB-1 and FIELD were identical. The HFST aggregates were obtained from the same delivered sample and the bonding agent was the same. The same contractor installed the materials on the pavement sections and laboratory test slabs during the same day. It is reasonable to conclude that the materials and installation are not a contributing factor to the test result differences.

Surface texture (LAB-1 CTM, FIELD CTM)

There was minimal change in LAB-1 CTM measurements after 70K TWPD cycles, as shown in Figure 8. FIELD CTM measurements generally trended to a terminal value after 1.5M ESALs as shown in Figure 16. Figure 38 displays the correlation between LAB-1 and FIELD terminal CTM values. The graph shows that the LAB-1 CTM values were higher than the FIELD CTM values and there was a reasonable correlation (R^2=0.88) between the values.

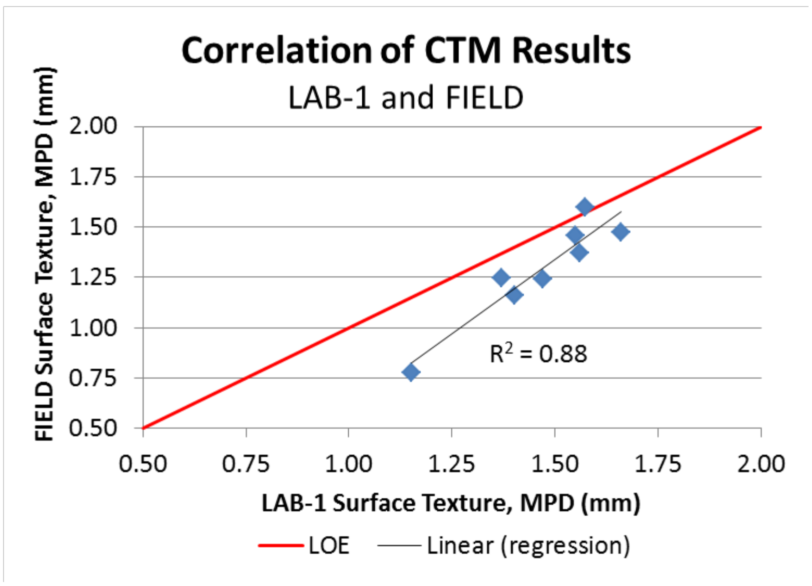
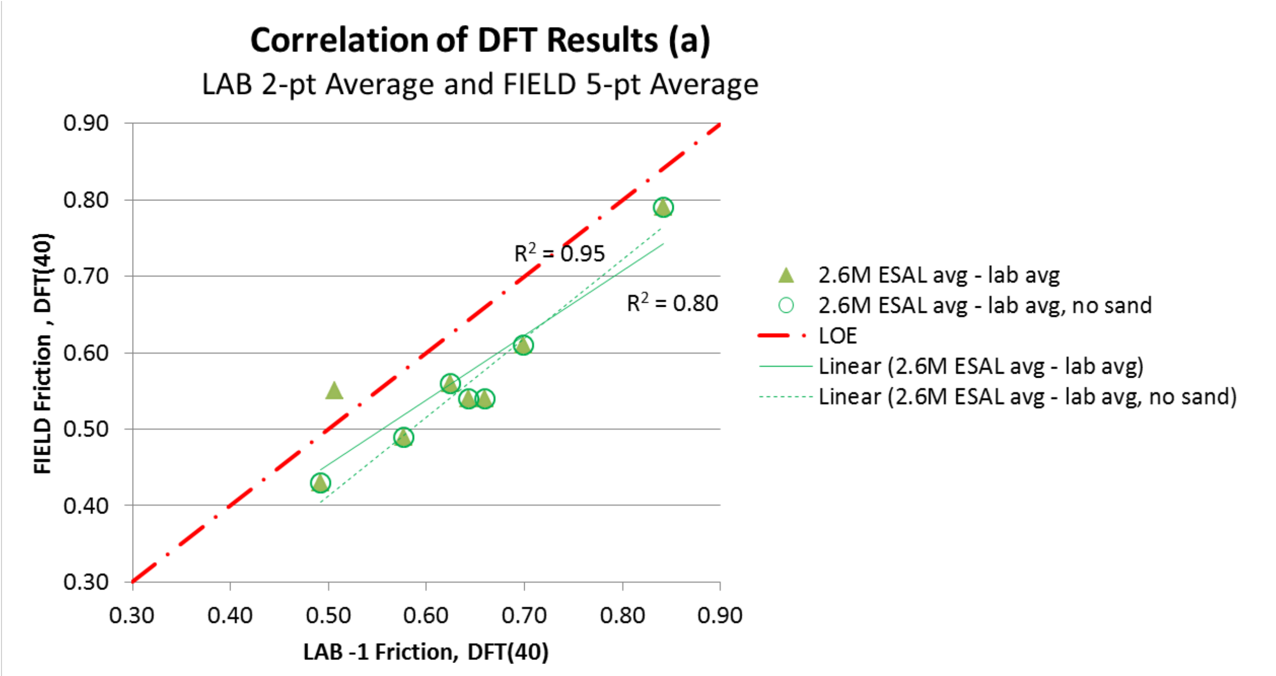


Figure 38 Correlation of LAB-1 CTM and FIELD CTM Terminal Surface Texture Measurements

Friction (LAB-1 DFT, FIELD DFT)

There was a measurable amount (6-8%) of friction loss in LAB-1 surfaces between 70K and 140K conditioning cycles, which indicates the surfaces were still polishing under the abrasion of the TWPD, as shown in Figure 9. Terminal LAB-1 DFT values were computed from the average of the 70K and 140K values with the recognition that the surfaces were still polishing. FIELD sections reached terminal friction within two months of the start of traffic conditioning, as shown in Figure 17. Three methods were used to define the FIELD terminal DFT friction. For all eight HFST, FIELD terminal DFT is based on the average of the last five values (up to 2.6M ESALs). For bauxite, granite, and flint, there are also two terminal values (at 2.6M and 10M ESALs) based on the linear trend of the data through 10M ESALs as previously shown in Figure 18. Figure 39 displays several correlations between LAB-1 terminal DFT and FIELD terminal DFT values. In general, LAB-1 DFT values are higher than FIELD DFT values as shown by the location of the data relative to the line-of-equality (LOE). Figure 39(a) uses the data through 2.6M ESALs for all eight HFST surfaces and achieves a linear correlation of 0.80; but there is one HFST aggregate (silica sand) that plots well outside the linear interpolation. When silica sand results were removed from the group, the correlation for the remaining seven surfaces increased to 0.95. Figure 39(b) narrows the comparison to the three surfaces tested over the extended 10M-ESALs period and achieves very high correlations (0.99 and 1.00). With the exception of the silica sand, LAB-1 DFT results correlated very well with FIELD DFT results. If LAB-1 terminal friction values were limited to the measurements at 140K TWPD conditioning cycles, the offset from the LOE would be slightly smaller.



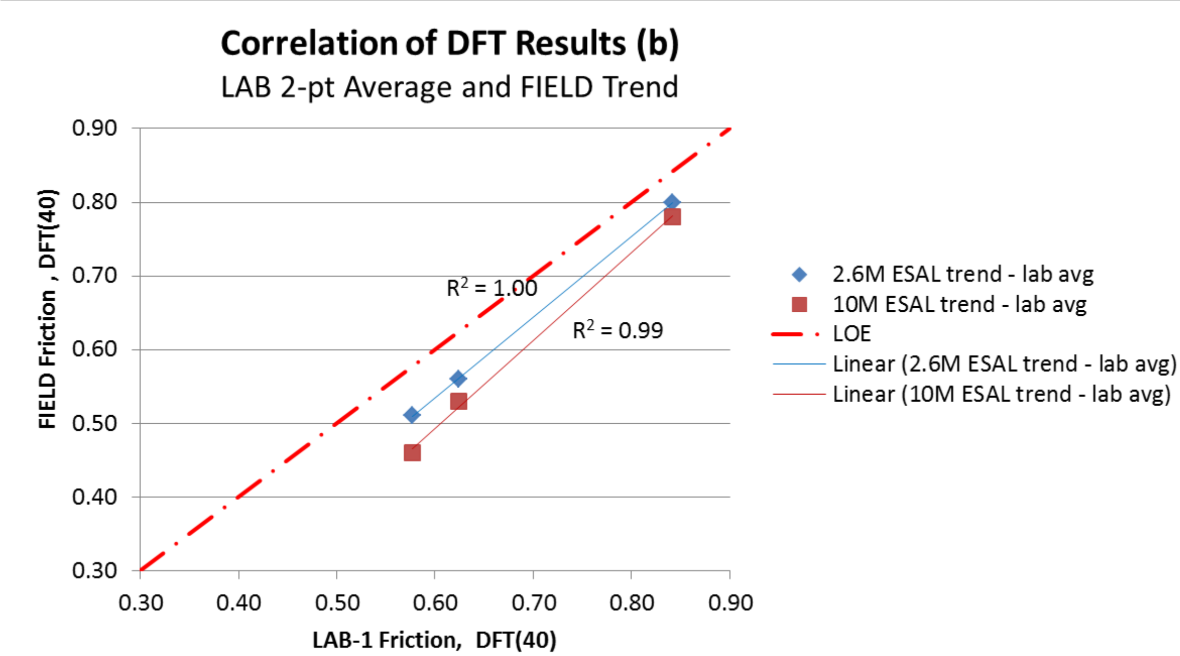


Figure 39 Correlation of LAB-1 DFT and FIELD DFT Terminal Friction Measurements
(a) based on FIELD average values, (b) based on FIELD trend values

Friction (LAB-1 DFT, FIELD DFT, FIELD Skid)

This evaluation combines a portion of the DFT results discussed above with FIELD skid trailer results. FIELD skid trailer SN40R measurements are restricted to three HFST surfaces and show declining values over the 10M ESALs traffic conditioning, as shown in Figure 19. Figure 40 displays the correlation between LAB-1 DFT and FIELD skid trailer data and between FIELD DFT and FIELD skid trailer. These comparisons are limited to three points and show correlations above 0.99. Using a LOE that matches DFT*100 to SN40R, the DFT values are higher than the skid trailer values. As an example, if a DFT is used in the field to measure bauxite HFST friction and records a value of 0.75, then the corresponding skid trailer measurement will be 60 to 65.

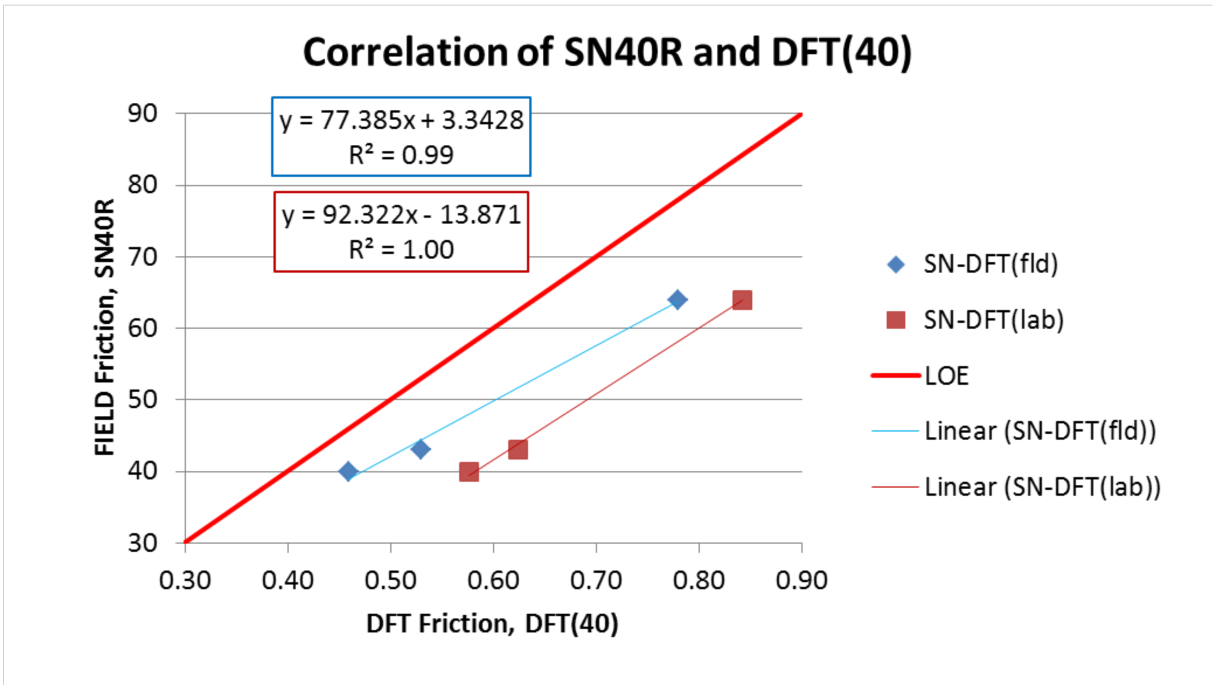


Figure 40 Correlation of LAB-1 DFT, FIELD DFT and FIELD Skid Trailer Terminal Friction Values

Texture – Friction Combined (LAB-1, FIELD, FIELD Skid)

The previous comparisons examined surface texture and friction as separate measurements. The results demonstrated a reasonable level of correlation between methods of measurement. The comparison became more complicated when the surface texture and friction data were combined to represent the performance of each aggregate. Figure 41 displays the combined results. The combined data did not show the same level of correlation. There were, however, a number of common observations. Results for bauxite were clearly unique compared to the performance of the other aggregates. In all cases, bauxite friction values were significantly higher while the surface texture values were toward the lower end of the group. FIELD CTM-DFT results (without the bauxite) displayed an increasing trend of surface texture and friction shown as the blue trend. LAB-1 CTM-DFT results did not have a strong trend, but would look better (as shown in the red trend) if both bauxite and silica sand were considered exceptions.

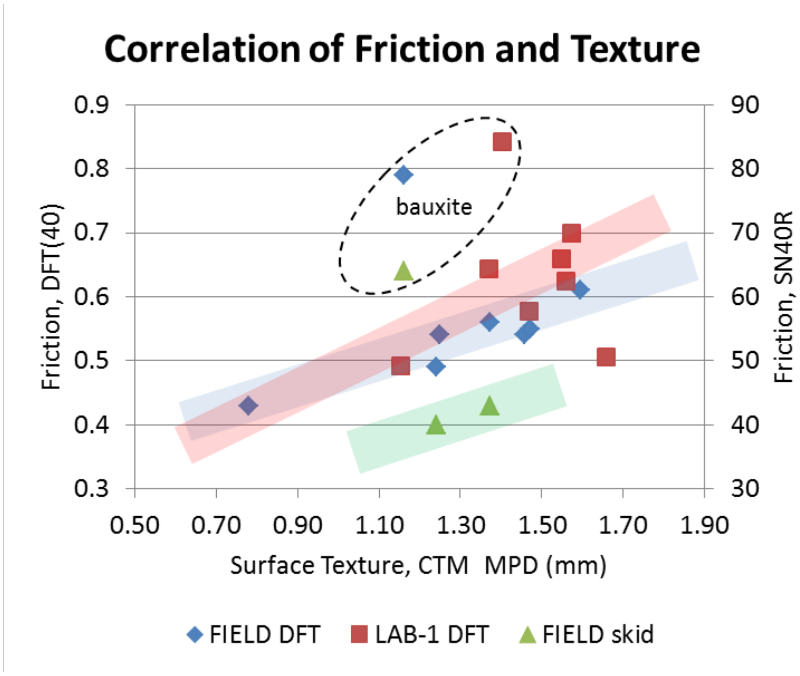


Figure 41 Comparison of Combined Texture and Friction Values

Highway agencies generally do not use defined friction values to classify pavement surfaces. There are defined values for classifying friction aggregates when friction is specified for pavement surface mixtures. This study was developed with the objective of comparing alternative aggregate sources to the HFST standard bauxite. The ranking of the aggregates based on measured friction are shown in Figure 42 and Table 8. None of the alternative aggregates matched the performance of the bauxite. The ranking of the silica sand varied the most between LAB-1 and FIELD results.

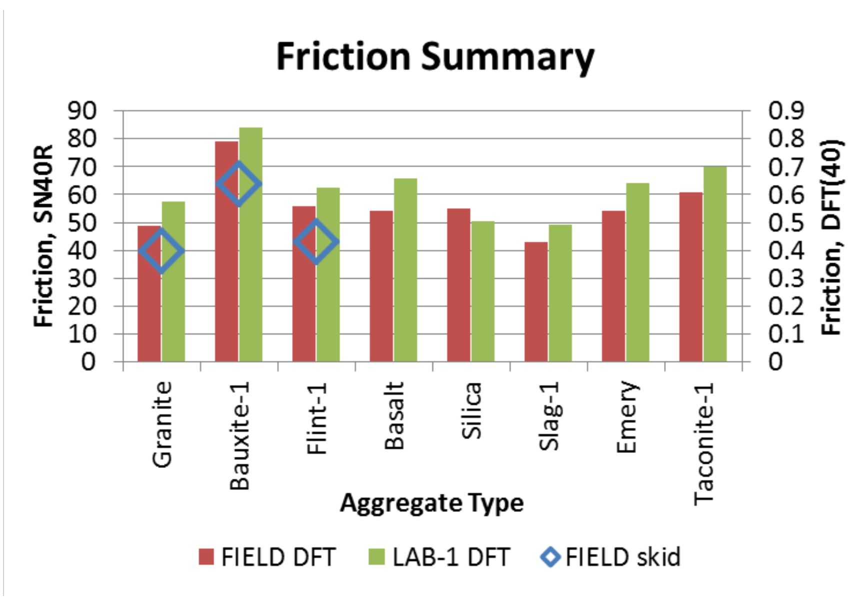


Figure 42 Summary of Terminal Friction Results

Table 8 Summary of Terminal DFT Friction Ranking

Rank	FIELD DFT(40)	Source	LAB-1 DFT(40)	Source
High	0.79	Bauxite-1	0.84	Bauxite-1
Medium	0.61	Taconite-1	0.70	Taconite-1
	0.56	Flint-1	0.66	Basalt
	0.55	Silica	0.64	Emery
	0.54	Basalt	0.62	Flint-1
	0.54	Emery	0.58	Granite
Low	0.49	Granite	0.51	Silica
	0.43	Slag-1	0.49	Slag-1

<u>LAB-1 and LAB-2 Comparisons</u>

The scope of LAB-2 was to determine if aggregate particle size influenced friction characteristics. The study selected four HFST aggregates for LAB-2 of which three were similar sources from LAB-1 and FIELD and one source was new. The three similar sources were bauxite, taconite, and flint. The new source was a different steel slag supplier.

Figure 43 compares the CTM results of LAB-1 and LAB-2. The results showed that the surface textures of the blended HFST gradations were similar to the textures of particles retained on the No. 12 sieve. The No. 8 and No. 12 particles dominated the blend, so this comparison agrees with the typical proportions used for HFST blended gradations. It can be concluded that the surface texture measurements are not comparable to the No. 8 particles because the finer No. 16 particles fill in a portion of the surface void space.

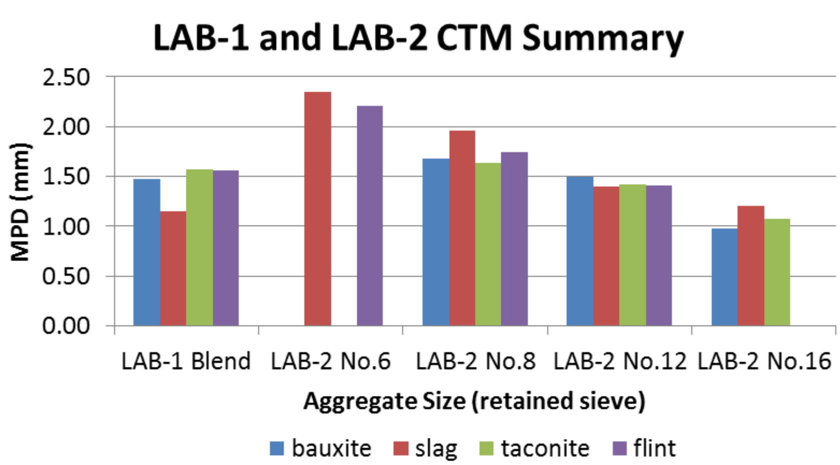


Figure 43 Comparison of LAB-1 and LAB-2 Surface Texture Measurements

LAB-1 and LAB-2 DFT results in Figure 44 show some similarities and some differences. In general, the ranking of friction between LAB-1 blends and Lab-2 screened aggregate surfaces agreed for bauxite (highest friction), taconite, and flint. The measured friction values for bauxite for LAB-2 slabs were higher than LAB-1 values, and the values for taconite and flint LAB-2 slabs were very similar to LAB-1 slabs. The key difference was the results for the steel slag aggregate. The slag source used for LAB-1 ranked very low (DFT=0.49) and the slag source for LAB-2 ranked very high (DFT range 0.87 to 0.93). The difference in friction performance was most likely due to differences in the characteristics of the steel slag.

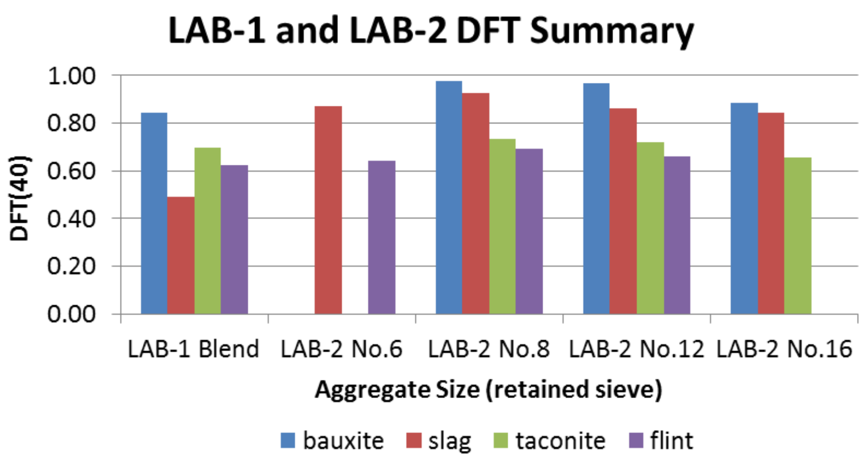


Figure 44 Comparison of LAB-1 and LAB-2 Friction Measurements

The results of LAB-2 showed some marginal increase in friction as the surface texture increased to 2.0 mm, as shown in Figure 31. In Figure 45, the CTM and DFT results of LAB-1 were added to LAB-2 results to observe the combined influence of surface texture and friction. LAB-1 bauxite results showed high friction (DFT=0.84), but the blend's single point result was lower than the LAB-2 curve. LAB-1 taconite and flint results showed a slightly lower friction for similar surface texture. The difference in the steel slag results is easily observed. Based on the trends for bauxite, taconite, and flint, it is probable that a blended HFST with LAB-2 steel slag source would generate a friction value between 0.75 and 0.80. It is also probable that a coarser blend of LAB-1 steel slag would not generate friction values above 0.60.

Similar to the LAB-1 and FIELD comparison, this study examined the ranking of the HFST aggregates based on LAB-1 and LAB-2 results. Table 9 presents the rankings of the two lab studies. The ranking for bauxite, taconite, and flint are the same as previously shown. The ranking of the steel slag in LAB-1 is low and the ranking of steel slag for LAB-2 is high due to the difference in aggregate sources.

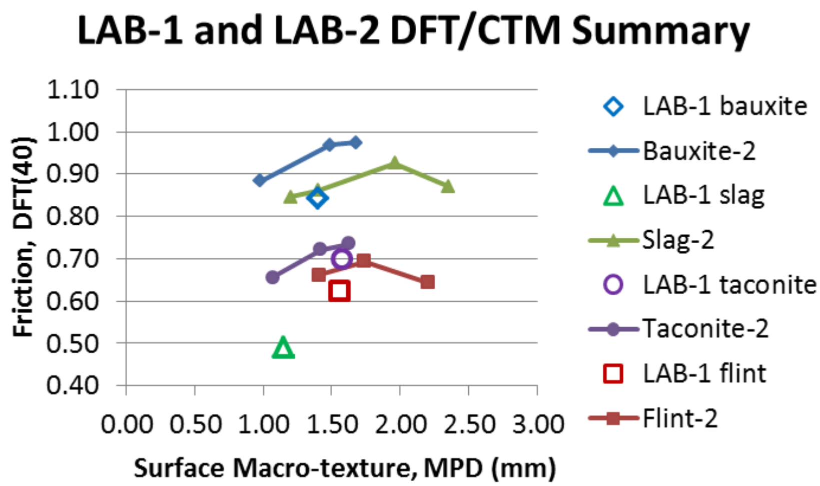


Figure 45 Summary of LAB-1 and LAB-2 Combined CTM and DFT Values

Table 9 Summary of LAB-1 and LAB-2 Friction Ranking

Rank	LAB-1 DFT(40)	Source	LAB-2 DFT(40) range	Source
High	0.84	Bauxite	0.88 to 0.97	Bauxite-2
	-	-	0.85 to 0.93	Slag-2
Medium	0.70	Taconite	0.66 to 0.74	Taconite-2
	0.62	Flint	0.64 to 0.69	Flint-2
Low	0.49	Slag	-	-

LAB-2 and FIELD Comparison

The comparison of LAB-1 to LAB-2 results showed that three aggregate types had similar results and the fourth aggregate, slag, varied significantly due to aggregate source differences. This final set of comparisons matched the range of results obtained in LAB-2 with FIELD results. Figure 46 displays LAB-2 range of values and FIELD terminal texture and friction combinations. FIELD texture and friction results are based on terminal values computed after 2.6M ESALs of traffic conditioning. Data shows that LAB-2 values had a greater offset than LAB-1 values from FIELD values. The slag results show the difference between two aggregate sources. The ranking of the aggregates based on these results is the same as shown in Table 9.

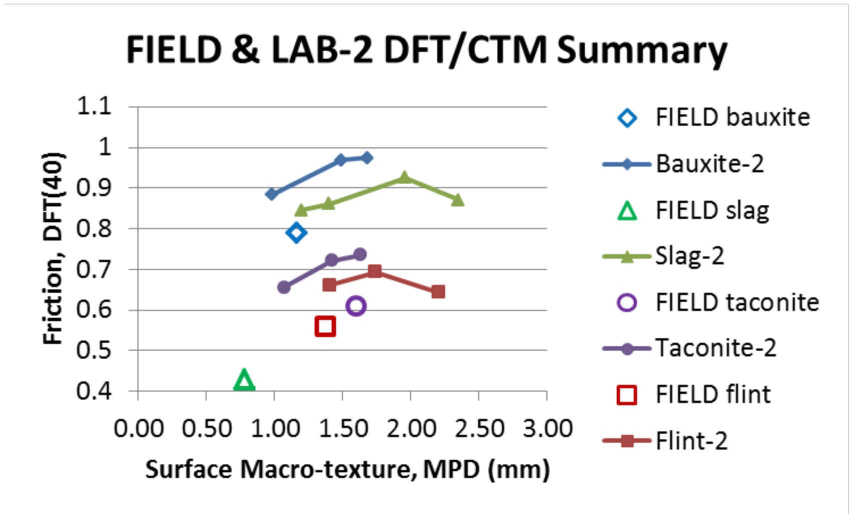


Figure 46 Comparison of LAB-2 and FIELD Combined CTM and DFT Values

CONCLUSIONS and RECOMMENDATIONS

This section of the report provides bulleted conclusions and recommendations for each portion of the study. Additional observations are made at the end about HFST specifications and testing.

Summary of LAB-1 Study

Eight aggregates were conditioned with the NCAT TWPD and tested with a CTM and DFT in the laboratory to compare seven alternative HFST aggregates to the standard bauxite HFST aggregate.

- The HFST samples caused significantly more wear on the TWPD tires and DFT slider pads than any conventional asphalt surface tested. This observation was expected for testing high friction surfaces.
- All eight surfaces maintained very good macro-texture (MPD > 1.0 mm) when compared to typical conventional asphalt dense-graded mix macro-texture values below 0.5 mm.
- CTM macro-texture did not significantly change between 70K and 140K TWPD conditioning cycles. For this study, the terminal MPD values were the average of the 70K and 140K values. Most terminal MPD values were 1.3 to 1.6 mm.
- DFT friction did decrease between 70K and 140K TWPD conditioning cycles, but the rate of change was much lower than the rate of change between 0K to 70K conditioning cycles. For this study, terminal DFT(40) values were the average of 70K and 140K values. The range of terminal DFT(40) values was 0.84 to 0.49.
- There was no correlation between terminal DFT and CTM values.

Summary of FIELD Study

- Three HFST aggregates (granite, bauxite and flint) were installed as 85 to 100-ft test sections to permit standard locked-wheel skid trailer measurements. The remaining aggregates were placed as 15-ft long test sections for CTM and DFT testing only.
- Surface conditioning (polishing) was accomplished by controlled truck traffic over two NCAT Pavement Test Track research cycles. All eight sections were subjected to 2.6M ESALs (approximately 350,000 18-wheel tractor trailer units) during the last quarter of the 2009 Test Track research cycle. The three 85 to 100-ft sections received an additional 8.0M+ ESALs during the 2012 research cycle.
- There was more measurement variability in FIELD test sections than in LAB-1 results. Additional variability in the data was expected in FIELD because there are no controls on weather, surface conditions, etc. Although the crew used the same process for installing FIELD and LAB-1 surfaces, the uniformity of placing the HFST aggregate over the larger FIELD area may have also been a contributing factor.
- Most sections reached terminal macro-texture before 1.5M ESALs. Terminal CTM MPD ranged from 1.6 to 0.8 mm. Most of the test surfaces had final CTM MPD values above 1.10 mm in the wheel path. These macro-texture values are very good compared to conventional HMA dense-graded mixes, with typical values below 0.5 mm.
- All sections reached terminal friction before 0.5M ESALs. Terminal DFT(40) friction values ranged from 0.79 to 0.43 based on measurements up to 2.6M ESALs. For the three 85 to 100-ft test sections, the trend in DFT friction values over extended traffic conditioning to 10M+ ESALs showed a slight additional decrease of 0.03 to 0.06 from the terminal values at 2.6M ESALs.

- Rankings of the eight HFST aggregates based on macro-texture and friction were different.
- Skid trailer friction measurements, SN40R, on the three 85 to 100-ft test sections started after 2.6M ESALS of conditioning. Bauxite friction values decreased from 70 to 64 over the additional 8.0M ESALs. Flint friction values decreased from 55 to 43. Granite friction values decreased from 55 to 40.

Summary of LAB-2 Study

- Bauxite, taconite, flint, and slag samples were screened into individual particle sizes to examine the impact of particle size on surface friction characteristics. Lab-2 slag was from a different source than the slag used in the LAB-1 and FIELD.
- CTM macro-texture changed from 2.3 mm to 1.0 mm as particle size changed from No. 6 to No. 16 sieve.
- Test slab surfaces with No. 8 particles (MPD 1.5-2.0 mm) measured highest friction values.
- DFT(40) friction decreased 0.10-0.15 as particle size dropped from No. 8 to No. 16 sieve. This could be related to the lower macro-texture of a surface with smaller particles.
- DFT(40) also decreased 0.08 as particles increased from the No. 8 to No. 6 sieve. This could be related to a reduced amount of contact area between DFT rubber sliders and a surface with larger particles.
- The Micro-Deval and AIMS tests measured the relative response of the four HFST aggregates.
- The results showed a correlation between Micro-Deval mass loss and HFST friction ranking for three aggregates. The fourth aggregate (flint) was a significant exception to the correlation.
- There was no correlation between friction and AIMS particle shape and angularity.
- The study was not able to develop a modified test procedure for the British Pendulum test for small No. 8 particles common in HFST aggregate blends. More work is needed to create a bond between the surface of the cured blank BP specimen coupon and bonding agent used to hold the aggregate to the surface of the blank coupon.

Summary of Study to Study Correlations

- There were good correlations between results for tests measuring the same surface characteristic.
    - Surface texture values after lab conditioning were typically 0.1-0.15 mm higher than after field conditioning. Lab conditioning is less aggressive than field abrasion.
    - Friction values using the DFT after lab conditioning were typically 0.10 higher than after field conditioning. DFT friction measured in the lab was influenced by a lower degree of polishing.
    - A field DFT(40) friction value of 0.60 is generally equivalent to a field skid trailer SN40R of 50. A DFT measures higher friction values than a locked-wheel skid trailer.

      $$SN40R = 77.4*DFT(40)_{FLD} + 3.3$$
    - A lab DFT(40) friction value of 0.70 is generally equivalent to a field skid trailer SN40R of 50. Both a lower degree of polishing in the laboratory and measurement differences between a DFT and skid trailer influenced the measured friction difference.

      $$SN40R = 92.3*DFT(40)_{LAB} - 13.9$$

- There was a marginal correlation for combined texture and friction results for each test condition. There were exceptions to observed trends for both high friction and low friction results.

- Based on the results of the three studies, measured friction for alternative HFST aggregates was not equal to bauxite. Figure 47 ranks the alternative HFST aggregates from high to low (left to right, respectively).
  - In Figure 47, the predicted FIELD skid values are computed from correlation with measured LAB-1 values.
  - In Figure 47, the slag-2 separate source was added with a predicted LAB-1 DFT(40) value of 0.75 for blended gradation based on the LAB-1 and LAB-2 comparison.
  - Field performance of silica sand was higher than LAB-1 performance and may rank higher than shown.

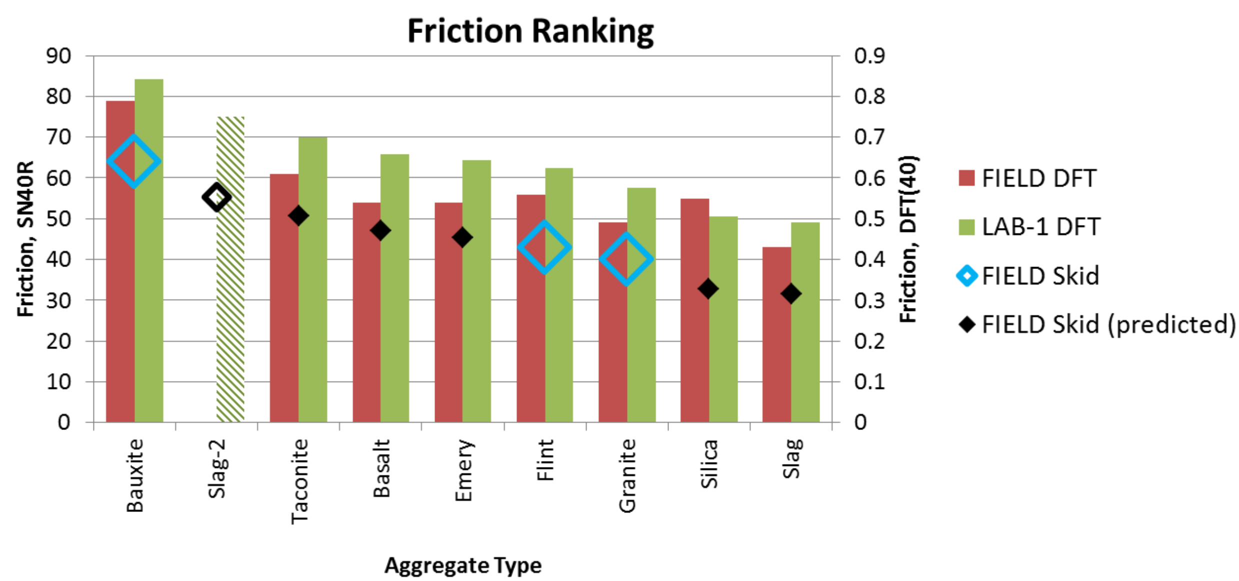


Figure 47 Summary Friction Ranking

<u>Tests for HFST Aggregate Samples</u>

- Agency specifications for qualifying HFST aggregate must be reasonable.
- Observations on tests used in this study:
  - The procedure for preparing laboratory specimens of loose aggregate samples for the British Pendulum and Wheel is restricted by particle size. The procedure needs to be modified to test No. 8 particles, a common HFST particle size. More research is needed to achieve this sample preparation modification.
  - The NCAT TWPD combined with CTM and DFT testing produced a reasonable correlation with field results when using single test parameters. There was no correlation when comparing combined CTM-DFT values. Laboratory terminal surface conditions should be measured after 140K TWPD cycles. Laboratory macro-texture and friction values were higher than field values. The use of the TWPD for surface friction comparisons is a developing analysis process. There are no “standards” or thresholds for CTM and DFT values. This test procedure provides the ability to make relative comparisons of surface friction performance between surfaces.

    - The Micro-Deval conditioning and AIMS test protocol did not correlate consistently with field friction results. More research may be warranted to examine exceptions noted in the results.

<u>Specifying Compliance for HFST Aggregates Specification</u>

- It is the responsibility of the governing agency to determine an acceptable threshold for HFST performance. The success (reduction in crashes) of locally placed sections with regionally available friction aggregate may be an appropriate approach for setting acceptable material thresholds.
- Post-construction/pre-traffic field tests should not be used for acceptance. This study showed that initial traffic reduced the measured DFT(40) friction value by 0.10-0.15. Measurements on the NCAT Pavement Test Track showed a gradual reduction in friction over time.
- For an end result specification, select minimum threshold values after a defined period of time. Three months is a reasonable time to delay testing after traffic has abraded the surface.
    - Minimum MPD=1.2 mm for surfaces texture
    - No acceptable minimum has been determined for friction. The criteria should indicate what test method will be used (SN40R or DFT(XX)). Aggregate acceptance criteria could be developed using a laboratory accelerated conditioning test.
- For a method specification, select aggregate type and gradation. A HFST gradation is influenced by aggregate size and blend proportions to achieve specified surface macro-texture and long-term particle bond.

<u>Further Study Needed</u>

Another study is needed to determine what an acceptable minimum friction should be for locations that warrant HFST. This study compared alternative friction aggregates placed as HFST to commonly specified bauxite HFST. Only one alternative aggregate displayed similar friction performance. This study showed that macro-texture and friction are not tied. Maintaining safe friction between a tire and pavement surface (micro-texture) and maintaining tire contact (macro-texture) are two functions. Further research is needed to separately measure the influence of pavement surface macro-texture and aggregate surface micro-texture on crash rate potential. In this study, standard friction testing with a locked-wheel skid trailer is used as an objective measure to correlate/predict crash rate potential (i.e., higher pavement surface friction has shown to reduce crash rates). Macro-texture and micro-texture each influence the crash rate potential. However, the relative degree to which macro-texture and micro-texture influence the crash rate potential is not documented, particularly at critical locations where HFST are typically placed. This further research could determine if regionally available friction aggregates (high quality, good micro-texture) used in the U.S. combined with high HFST pavement surface macro-texture would reduce crash rates comparable to HFST with bauxite.

More work is needed on a modification of the laboratory sample preparation for use of the British Pendulum and Wheel. The sample preparation needs to create a bond between the surface of the cured blank BP specimen coupon and the bonding agent used to hold the aggregate to the surface of the blank coupon. The two bonding agents must be compatible so that the second bonding agent will adhere to a cured agent used to form the blank BP specimen coupon.

More evaluation of the use of the Micro-Deval and AIMS for HFST aggregate classification is needed. The Micro-Deval conditioning showed continued mass loss after 50 minutes. The conditioning time should be extended to determine the length of time required to identify a reduction in the rate of mass loss to define a terminal mass loss period. A study is needed to determine why the flint aggregate was a significant exception to the friction-mass loss trend. A study should expand the number of aggregate sources to determine the strength of the correlation to field friction performance.

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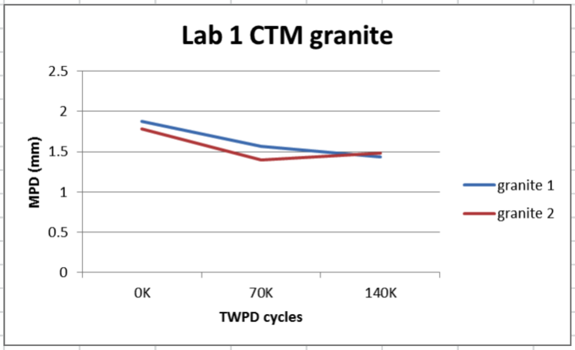
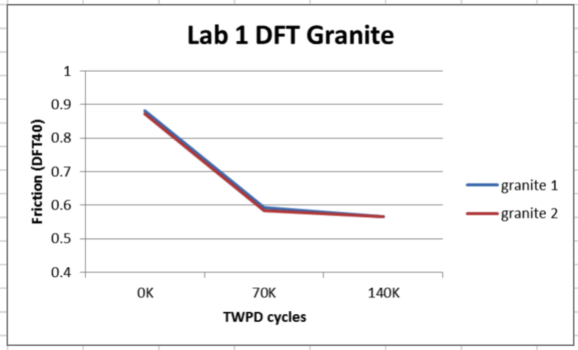
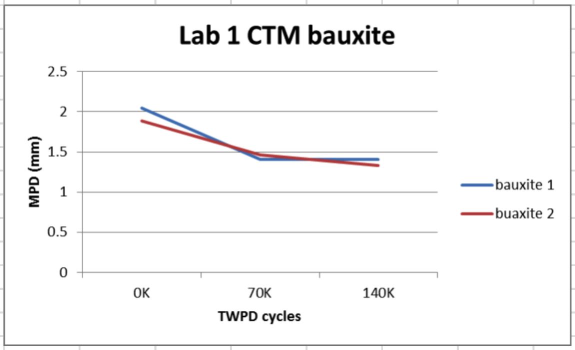
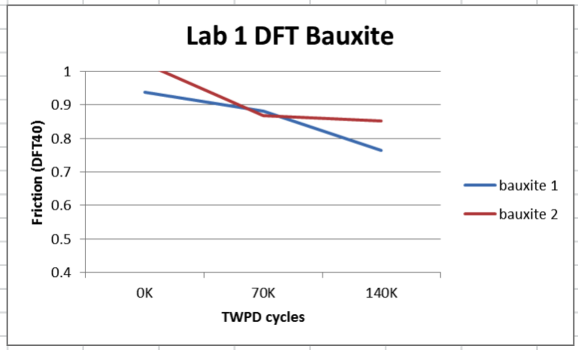
Vollor, T. and Hanson, D. Development of Laboratory Procedure for Measuring Friction of HMA Mixtures Phase I, NCAT Report 06-06, 2006

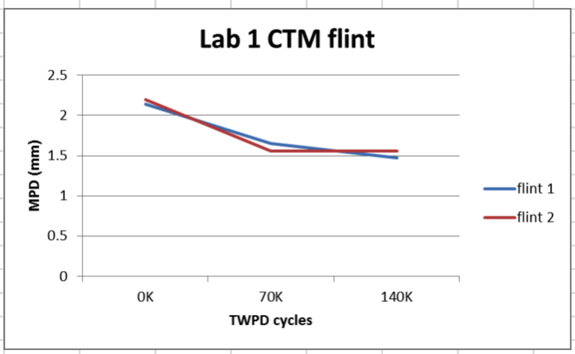
APPENDIX-A FIRST LAB STUDY RESULTS

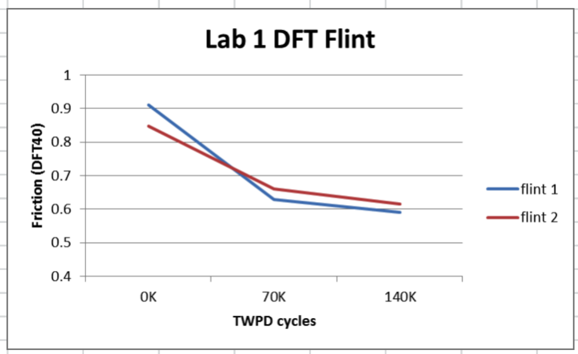


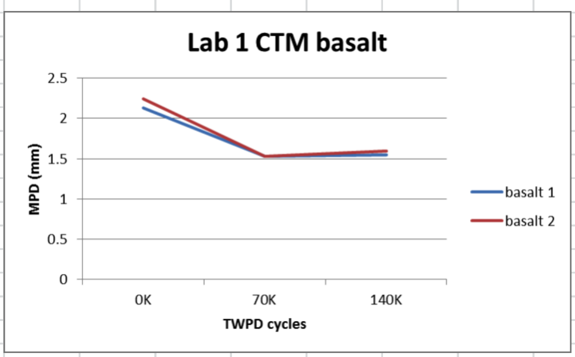


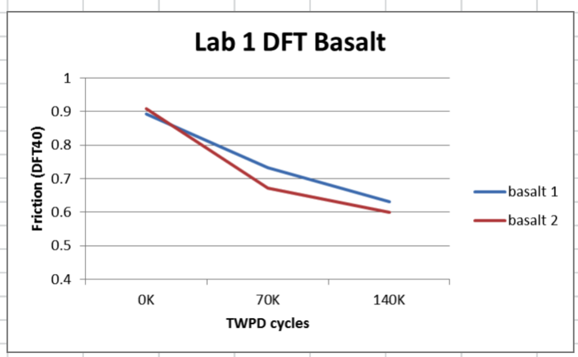


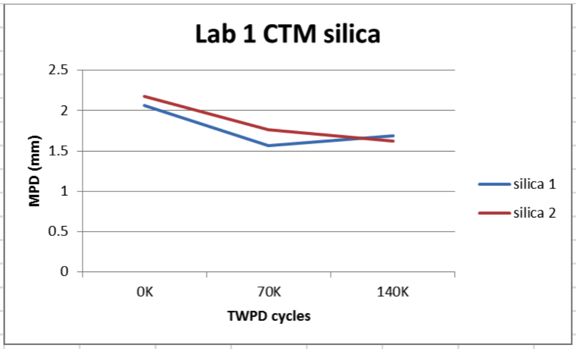


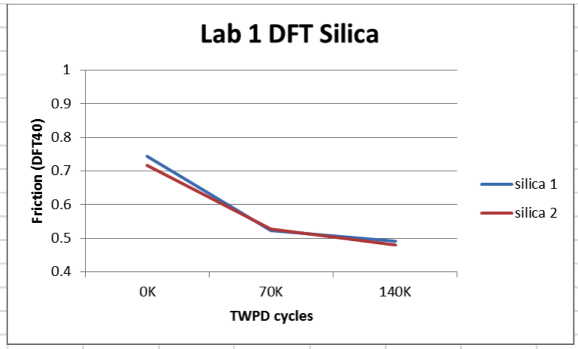


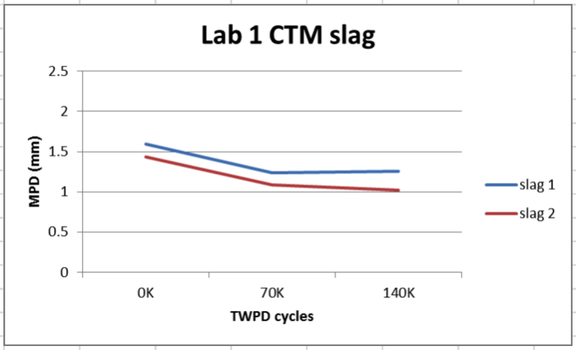


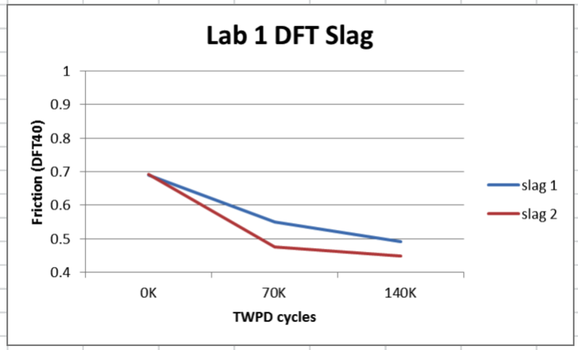


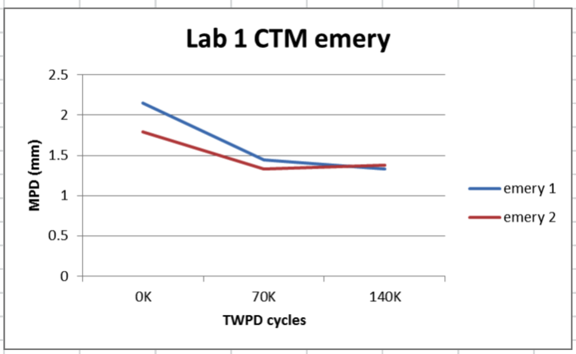


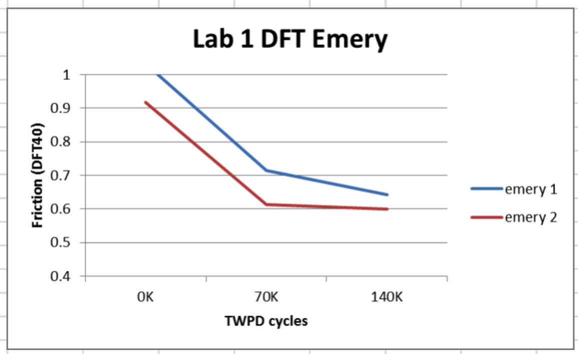

Lab 1 CTM silica
MPD (mm)
2.5
2
1.5
1
0.5
0
0K
70K
140K
TWPD cycles
silica 1
silica 2

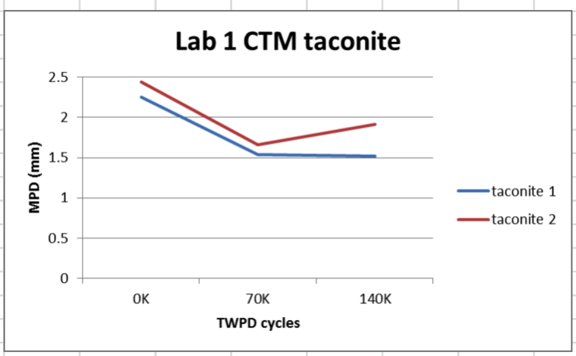

Lab 1 DFT Silica
Friction (DFT40)
1
0.9
0.8
0.7
0.6
0.5
0.4
0K
70K
140K
TWPD cycles
silica 1
silica 2

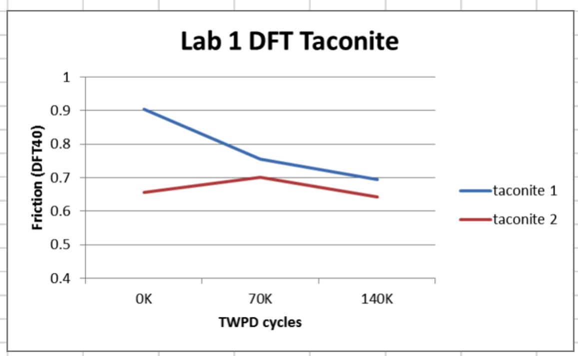

Lab 1 CTM slag
MPD (mm)
2.5
2
1.5
1
0.5
0
0K
70K
140K
TWPD cycles
slag 1
slag 2


Lab 1 DFT Slag
Friction (DFT40)
1
0.9
0.8
0.7
0.6
0.5
0.4
0K
70K
140K
TWPD cycles
slag 1
slag 2

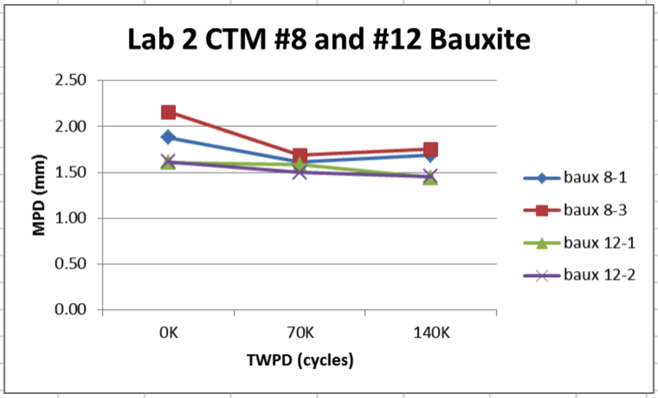

Lab 1 CTM emery
MPD (mm)
2.5
2
1.5
1
0.5
0
0K
70K
140K
TWPD cycles
emery 1
emery 2

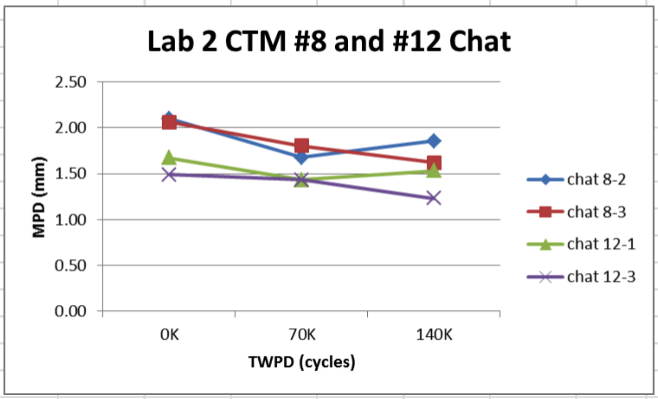

Lab 1 DFT Emery
Friction (DFT40)
1
0.9
0.8
0.7
0.6
0.5
0.4
0K
70K
140K
TWPD cycles
emery 1
emery 2

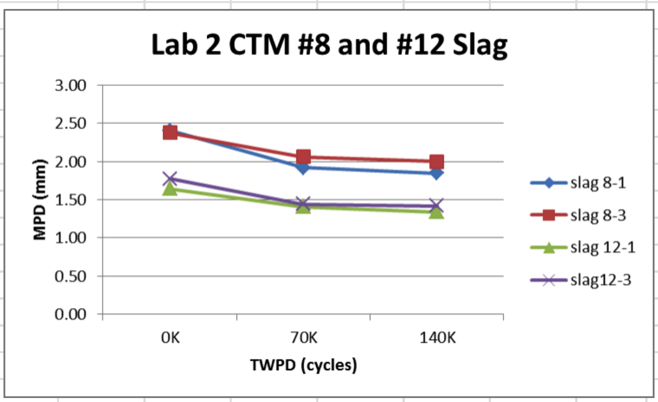

Lab 1 CTM taconite
MPD (mm)
2.5
2
1.5
1
0.5
0
0K
70K
140K
TWPD cycles
taconite 1
taconite 2

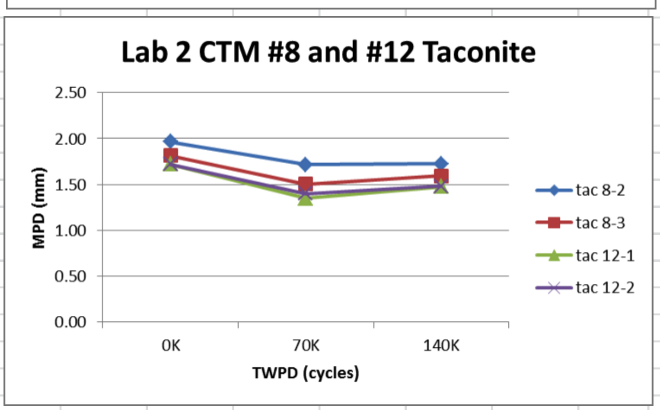

Lab 1 DFT Taconite
Friction (DFT40)
1
0.9
0.8
0.7
0.6
0.5
0.4
0K
70K
140K
TWPD cycles
taconite 1
taconite 2

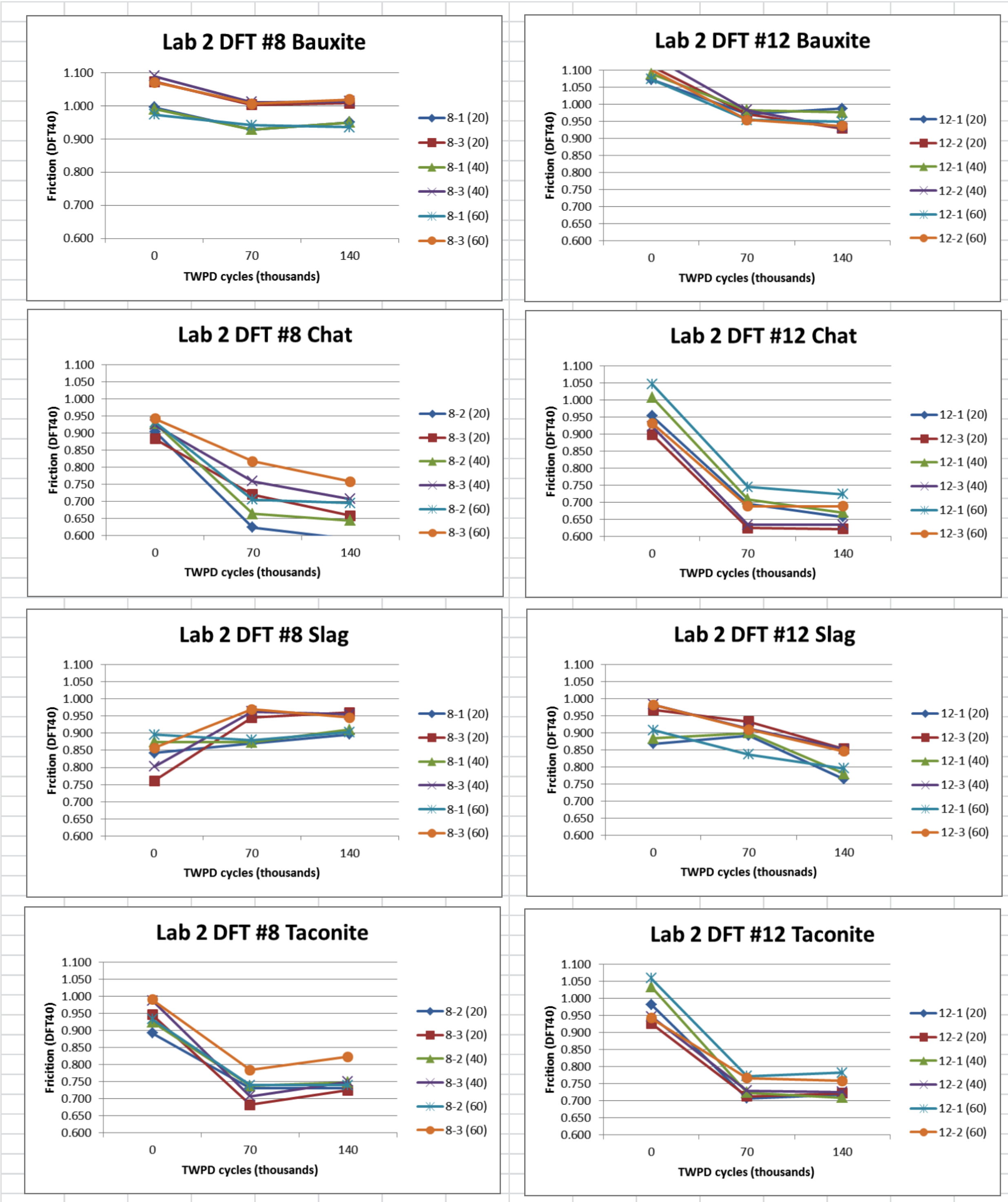
APPENDIX-B SECOND LAB STUDY RESULTS

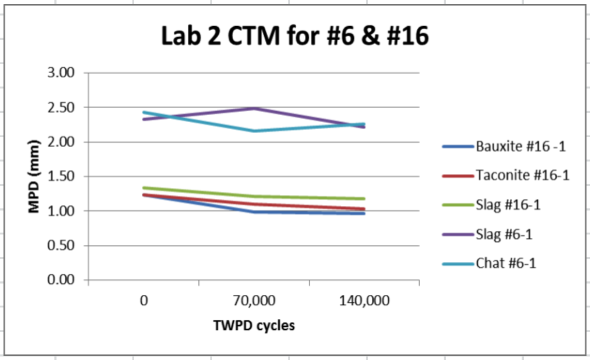


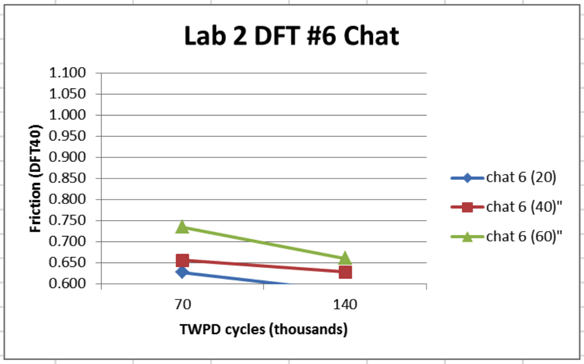


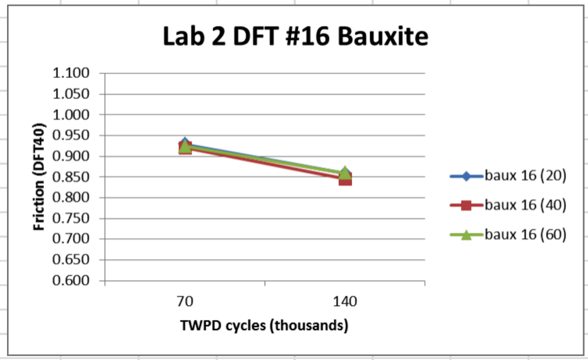


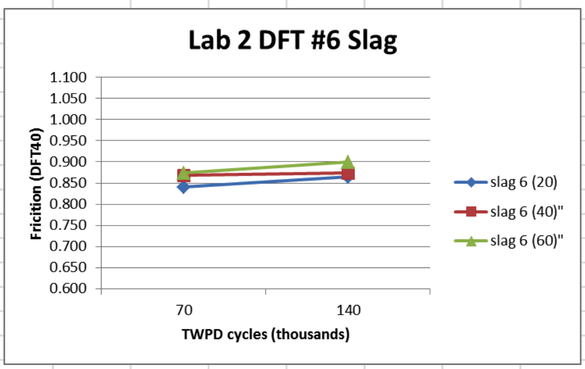


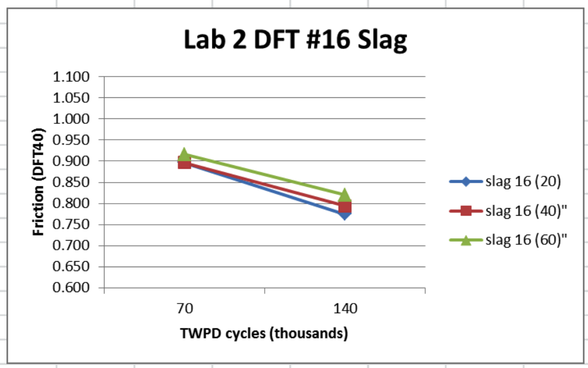

Lab 2 DFT #8 Bauxite
Friction (DFT40)
1.100
1.000
0.900
0.800
0.700
0.600
0
70
140
TWPD cycles (thousands)
8-1 (20)
8-3 (20)
8-1 (40)
8-3 (40)
8-1 (60)
8-3 (60)
Lab 2 DFT #12 Bauxite
Friction (DFT40)
1.100
1.050
1.000
0.950
0.900
0.850
0.800
0.750
0.700
0.650
0.600
0
70
140
TWPD cycles (thousands)
12-1 (20)
12-2 (20)
12-1 (40)
12-2 (40)
12-1 (60)
12-2 (60)
Lab 2 DFT #8 Chat
Friction (DFT40)
1.100
1.050
1.000
0.950
0.900
0.850
0.800
0.750
0.700
0.650
0.600
0
70
140
TWPD cycles (thousands)
8-2 (20)
8-3 (20)
8-2 (40)
8-3 (40)
8-2 (60)
8-3 (60)
Lab 2 DFT #12 Chat
Friction (DFT40)
1.100
1.050
1.000
0.950
0.900
0.850
0.800
0.750
0.700
0.650
0.600
0
70
140
TWPD cycles (thousands)
12-1 (20)
12-3 (20)
12-1 (40)
12-3 (40)
12-1 (60)
12-3 (60)
Lab 2 DFT #8 Slag
Frcition (DFT40)
1.100
1.050
1.000
0.950
0.900
0.850
0.800
0.750
0.700
0.650
0.600
0
70
140
TWPD cycles (thousands)
8-1 (20)
8-3 (20)
8-1 (40)
8-3 (40)
8-1 (60)
8-3 (60)
Lab 2 DFT #12 Slag
Frcition (DFT40)
1.100
1.050
1.000
0.950
0.900
0.850
0.800
0.750
0.700
0.650
0.600
0
70
140
TWPD cycles (thousnads)
12-1 (20)
12-3 (20)
12-1 (40)
12-3 (40)
12-1 (60)
12-3 (60)
Lab 2 DFT #8 Taconite
Frcition (DFT40)
1.100
1.050
1.000
0.950
0.900
0.850
0.800
0.750
0.700
0.650
0.600
0
70
140
TWPD cycles (thousands)
8-2 (20)
8-3 (20)
8-2 (40)
8-3 (40)
8-2 (60)
8-3 (60)
Lab 2 DFT #12 Taconite
Frcition (DFT40)
1.100
1.050
1.000
0.950
0.900
0.850
0.800
0.750
0.700
0.650
0.600
0
70
140
TWPD cycles (thousands)
12-1 (20)
12-2 (20)
12-1 (40)
12-2 (40)
12-1 (60)
12-2 (60)

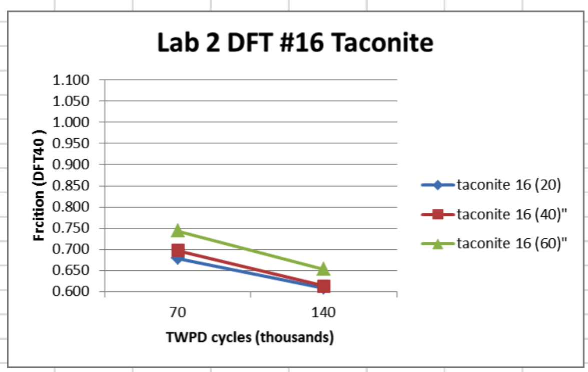

Lab 2 CTM for #6 & #16
MPD (mm)
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
70,000
140,000
TWPD cycles
Bauxite #16 -1
Taconite #16-1
Slag #16-1
Slag #6-1
Chat #6-1


Lab 2 DFT #6 Chat
Friction (DFT40)
1.100
1.050
1.000
0.950
0.900
0.850
0.800
0.750
0.700
0.650
0.600
70
140
TWPD cycles (thousands)
chat 6 (20)
chat 6 (40)"
chat 6 (60)"


Lab 2 DFT #16 Bauxite
Friction (DFT40)
1.100
1.050
1.000
0.950
0.900
0.850
0.800
0.750
0.700
0.650
0.600
70
140
TWPD cycles (thousands)
baux 16 (20)
baux 16 (40)
baux 16 (60)


Lab 2 DFT #6 Slag
Fricition (DFT40)
1.100
1.050
1.000
0.950
0.900
0.850
0.800
0.750
0.700
0.650
0.600
70
140
TWPD cycles (thousands)
slag 6 (20)
slag 6 (40)"
slag 6 (60)"


Lab 2 DFT #16 Slag
Friction (DFT40)
1.100
1.050
1.000
0.950
0.900
0.850
0.800
0.750
0.700
0.650
0.600
70
140
TWPD cycles (thousands)
slag 16 (20)
slag 16 (40)"
slag 16 (60)"


Lab 2 DFT #16 Taconite
Frcition (DFT40)
1.100
1.050
1.000
0.950
0.900
0.850
0.800
0.750
0.700
0.650
0.600
70
140
TWPD cycles (thousands)
taconite 16 (20)
taconite 16 (40)"
taconite 16 (60)"