DEPARTMENT OF TRANSPORTATION

Taconite As a Lower-Cost, Alternative High-Friction Surface Treatment to Calcined Bauxite for Low Volume Roads in Minnesota

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16. Abstract (Limit: 250 words)

This four+ year project (2020-2025) assessed whether friction aggregate produced from a byproduct generated by Minnesota's taconite (iron ore) mining industry can provide adequate or comparable skid resistance performance to calcined bauxite in high friction surface treatment (HFST)-type applications. Six pavement test sections approximately 1/10th of a mile (160 meters) in length were established at a low volume road location northwest of Duluth, Minnesota. Two epoxy-based HFST-equivalent test sections using taconite and calcined bauxite aggregate were the project's focus. Three test sections of GSB (gilsonite)-based pavement preservation surface treatments utilizing a slightly finer gradation of taconite friction aggregate were also installed, while a section of existing chipseal pavement acted as the control. Friction properties were measured twice a year using a dynamic friction tester (DFT) and a British Pendulum (BP) Skid Resistance tester, while the Minnesota Department of Transportation's (MnDOT's) locked-wheel pavement friction tester (LWPFT) was used a minimum of once a year. Supplemental laboratory and environmental testing and a life cycle assessment (LCA) of HFST systems utilizing taconite and bauxite aggregate were also performed, as was a demonstration of SCRIM (Sideway-force Coefficient Routine Investigation Machine) technology. Taconite and calcined bauxite HFST test sections produced the highest friction numbers, about 40 to 50% higher than the chipseal control. Taconite's friction numbers averaged 6% lower than calcined bauxite's and exhibited virtually no divergence from calcined bauxite's friction numbers over time. Collectively, project findings suggest that taconite aggregate can provide comparable friction performance to calcined bauxite, at a significantly smaller environmental footprint.

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Executive Summary

Taconite rock from Minnesota's Mesabi Iron Range is one of the hardest natural geological materials that can be used as friction aggregate. Calcined bauxite is an even harder synthetic, ceramic-like friction aggregate which has been given a preferred status relative to HFST usage by the Federal Highway Administration (FHWA). However, calcined bauxite is energy-intensive to produce, expensive, and often imported from overseas. With the support of the Minnesota Local Road Research Board (LRRB) and the Minnesota Department of Transportation (MnDOT), a four+ year (2021-2025) project was undertaken to assess whether friction aggregate produced from a fine aggregate-equivalent byproduct generated by Minnesota's taconite (iron ore) mining industry can provide adequate skid resistance performance comparable to calcined bauxite in high friction surface treatment (HFST) applications.

In coordination with St. Louis County, six pavement test sections – each approximately 0.1 mile (160 meters) in length – were established at a low volume road location northwest of Duluth, Minnesota. Test sections included two epoxy-based HFST sections using taconite and calcined bauxite aggregate (they were the project's focus); three non-HFST, gilsonite-based (GSB) asphaltic emulsion test sections (as an alternative to micro surfacing) that used a finer gradation of taconite aggregate to enhance its friction characteristics; and a control (existing chipseal pavement). Each section's friction properties were measured using a dynamic friction tester (DFT), a British Pendulum (BP) Skid Resistance tester, and MnDOT's locked-wheel pavement friction tester (LWPFT). DFT and BP tests were conducted twice a year, in the spring and fall, and the LWPFT a minimum of once a year. Supplemental laboratory and environmental testing and a life cycle assessment (LCA) of HFST systems utilizing taconite and bauxite aggregate were also performed, as was a July 2024 demonstration of SCRIM (Sideway-force Coefficient Routine Investigation Machine) technology.

Key project findings are summarized as follows:

1. The taconite and calcined bauxite HFST test sections produced the highest friction numbers, averaging about 40 to 50% higher than the chipseal control.

2. DFT and LWPFT results for the taconite and calcined bauxite HFST test sections and the control section were highly correlated (R^2 of 0.98).

3. Taconite's friction numbers were close to calcined bauxite's, averaging 6% lower throughout the project, and exhibited virtually no divergence from calcined bauxite's friction numbers over time, suggesting the two aggregates wear and maintain their friction characteristics similarly.

4. Two of the GSB (test sections produced friction numbers comparable to and slightly higher than the control.

5. The BP results exhibited greater variability and often showed weak to no correlation with the DFT results on an individual test and test section basis. However, a comparison of the composite average results of BPs and DFTs over 4+ years of data on all test sections shows

weak/fair to good correlation (R^2 of 0.26 to 0.59), depending on the time range compared within the 4-year project period.

6. The July 2024 SCRIM test results showed good agreement with the DFT and locked wheel pavement friction tester. Like the LWPFT, the SCRIM requires no traffic control. But unlike the LWPFT, the SCRIM can test short pavement intervals and horizontal curves.
7. A life cycle assessment (LCA) showed that an HFST system using taconite aggregate had between 55% (Ecosystems) and 31% (Resources) fewer impacts across all impact categories than an HFST system using calcined bauxite and showed that the environmental impact of taconite friction aggregate production was 2 to 3 orders of magnitude lower than that of calcined bauxite aggregate production. These LCA findings have potential implications relative to environmental product declaration (EPD) considerations.

Collectively, these project findings suggest that taconite (Mesabi) aggregate can provide comparable friction performance to calcined bauxite and at a smaller environmental footprint, giving end users an alternative pavement surface treatment aggregate option to consider in their decision-making processes.

As a follow-up, maintaining the project's CSAH 15 pavement treatment sections for continued testing after the current project ends should be considered for monitoring long-term (> 5 years) performance. New installations, especially on horizontal curves having a higher ADT and where tangential forces are greatest (and where HFSTs are most often applied), would provide another means to generate additional quantitative data for further assessing the field performance of taconite friction aggregate. The July 2024 demonstration of SCRIM technology showed that it can generate detailed friction and pavement texture information over short distances and along horizontal curves, a testing methodology and capability that future projects should consider incorporating into their work plans. Another potentially useful aggregate material assessment and comparison tool to consider using on future related projects is the UMN Department of Civil, Environmental, and Geo-Engineering's advanced particle analyzer.

Going forward, taconite friction aggregate should probably be referred to something other than an HFST material, because the HFST classification (or "brand") applies to calcined bauxite, as indicated in FHWA research (Merritt et al., 2021). The minimum aluminum oxide requirement that has been written into HFST spec sheets is instructive on this point because no other natural aggregate material can possibly meet that minimum spec other than calcined bauxite. Therefore, referring to taconite as – for example – an "Enhanced Friction Treatment (EFT)" alternative to HFST should be considered as a future descriptor.

Chapter 1: Introduction

1.1 Introduction

The project's motivation is described best in the 2020 work plan abstract:

"Real field data are lacking for a direct comparative performance evaluation of Mesabi (taconite) friction aggregate and calcined bauxite in high friction surface treatments (HFST) applications. Calcined bauxite has been given a preferred status relative to HFST usage by FHWA, but it is imported, expensive, and energy-intensive to produce. A recycled/byproduct alternative, like Mesabi HFST aggregate, may provide adequate or comparable field skid resistance performance and it is significantly less energy-intensive to produce."

The investigators felt it was necessary to perform an investigation at the roadway scale, where both aggregates were subjected to identical traffic, climate, and maintenance (i.e., snow plowing) conditions. Therefore, the project's primary focus was to install typical epoxy-based HFST systems using both aggregate types on a segment of a low volume road northwest of Duluth in St. Louis County, MN. Also installed were three asphaltic (non-HFST) pavement preservation surface treatments that used a finer gradation of taconite aggregate.

This chapter provides an overview of the project's objectives, research approach, implementation, and testing. Chapters 2 to 7 summarize the research performed and the findings of the project's major tasks:

- Chapter 2: Literature review
- Chapter 3: Identification of HFST Contractor, and Acquiring Materials
- Chapter 4: Laboratory Testing of Materials
- Chapter 5: Test Section Preparation and Installation
- Chapter 6: Collection, Quantification, and Characterization of Fugitive Dust Particulate Matter (PM)
- Chapter 7: Pavement Test Section Monitoring and Testing
- Chapter 8: Summary, Conclusions and Recommendations

1.2 Expected Research Benefits

The project began in August of 2020, following receipt of an executed contract and Notice of Grant/Contract Award (NOGA).

As described in the project workplan, anticipated project benefits included:

- Environmental (use of a by-product/recycled aggregate product produced in Minnesota);
- Enhanced safety at more locations;
- Raw material cost savings;
- Operational and maintenance savings via the pavement preservation aspects of HFST; and

- Potentially improved lifecycle costs.

1.3 Documentation of Methodology

The project's Kickoff Technical Advisory Panel (TAP) meeting (Appendix A) took place on June 3, 2020, where the project workplan and strategy was presented by the project Principal Investigator (PI) and discussed among the project team and the TAP. Follow-up TAP meetings were held on August 8, 2022, and March 29, 2023, to review and discuss the project's progress and findings. A series of Task reports (chapters 2 to 7) have documented each completed project activity/task, while quarterly reports have been regularly submitted to the Center for Transportation Studies (CTS), via its For CTS Researchers portal.

The following steps were taken to implement, document, and evaluate the technical, environmental, and economic aspects of the project:

- Installation of two HFST test sections using calcined bauxite and Mesabi (taconite) friction aggregate
- Installation of three non-HFST, gilsonite-based asphaltic emulsion (GSB) test sections as an alternative to micro surfacing that used a finer gradation of taconite aggregate to enhance its friction characteristics
- Biannual friction testing of test sections using a dynamic friction tester (DFT) and a British Pendulum (BP) Skid Resistance tester, while the Minnesota Department of Transportation's (MnDOT's) locked-wheel pavement friction tester (LWPFT) was used a minimum of once a year. A special demonstration of SCRIM (Sideway-force Coefficient Routine Investigation Machine) technology was arranged by the project team and took place on July 26th of 2024.
- Select laboratory testing of pavement specimens and characterization of HFST aggregates
- Presentation of project results at meetings and conferences

1.4 Implementation Steps

The project's test location is CSAH-15 (Munger Shaw Road) in St. Louis County. As Figure 1.1 shows, the location is just northwest of Duluth, near US Hwy 53.

With the existing chip-sealed pavement acting as the control (Test Section 0), four surface-treated pavement test sections were installed on July 29, 2021 (chapter 5). A fifth test section (Test Section 5) was added on August 5, 2022. Each surface-treated test section was a minimum of 475 feet in length and 11 feet in width. The test sections were installed in the northbound lane of CSAH-15, just past a horizontal curve (Curve #015D) that received a calcined bauxite surface treatment in late July of 2020. The five surface-treated test sections consist of the following, as shown from south to north in Figure 1.2:

- Test Section 1: Taconite applied using a standard gradation GSB-based system (GSB-8, or GSB 8)

- Test Section 2: Taconite applied using a GSB-based system at a slightly coarser gradation than Test 1 (GSB-6, or GSB 6)
- Test Section 3: Taconite applied with epoxy/resin – Typical HFST installation (HFST Tac)
- Test Section 4: Bauxite applied with epoxy/resin – Typical HFST installation (HFST Baux)
- Test Section 5: Taconite applied using a standard gradation GSB-based system (New GSB -8, or New GSB), but at a higher aggregate application rate

Figure 1.1. Project location reference map

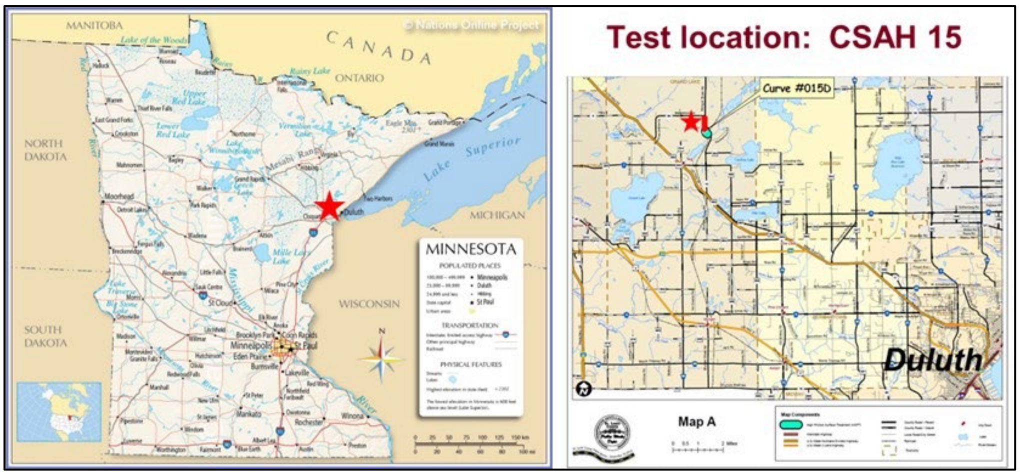
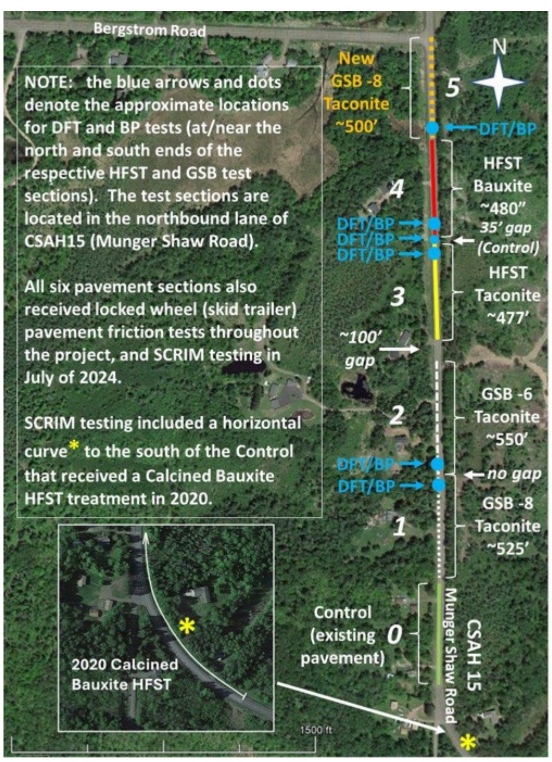


Figure 1.2. Project test site location map showing Control (0) and pavement surface treatment test sections 1 to 5, DFT and BP testing locations, and horizontal curve #015D included in the July 2024 SCRIM testing (*inset)



Chapter 2: Literature review

2.1 Introduction

In this task, the investigators conducted a review of literature/past studies/commercial product information and specification sheets (academic, agency, and industry) related to high friction surface treatment (HFST). HFST is a method of increasing the skid resistance of pavements in order to reduce crashes and loss of control of vehicles at horizontal road curves. HFST has been recently introduced in the United States and has been implemented in various states on numerous road sections.

The PI and NRRI have a long history of researching the aggregate potential of by-product materials generated by Minnesota's iron ore (taconite) mining industry (Zanko et al., 2003, 2009, 2010, 2012 and Zanko and Fosnacht, 2016), and value-added friction aggregates, derived from taconite tailings, have been an area of focus. For example, as a result of NRRI's work, a small Mesabi Iron Range company is now producing friction aggregate for use in bridge deck overlay systems. The aggregates are currently used on several bridge projects in Pennsylvania.

Mesabi friction aggregates (taconite) were included in an NCAT study of HFST aggregates (Heitzman et al., 2015), and the laboratory testing results showed that these aggregates were the best-performing of all the natural aggregates included in the study. Calcined bauxite (a synthetic aggregate) was the best performer, overall. Mesabi friction aggregate's applicability for HFST projects needs investigation, especially in comparison to the more expensive calcined bauxite, which represents the main goal of this project.

2.2 Literature Review

A considerable body of work exists about high friction surface treatments (HFST). A recent Transportation Research Synthesis for HFST was done for LRRB/MnDOT (CTC & Associates LLC, 2018a, 2018b), in which "…selected state departments of transportation were surveyed about their practices and experience with HFST applications, including materials specifications, locations that benefit most from HFST, the pavement treatment's durability and the resulting impact on safety." This work was conducted to inform MnDOT and local transportation agencies in Minnesota about HFST.

The effectiveness of HFST on reducing crashes by increasing skid resistance was studied by Li et al. (2016). As part of their research, sponsored by the Federal Highway Administration, Li et al. compiled comprehensive pavement surface data, taken at various HFST sites in 11 states. Measurements of pavement friction were obtained, for both untreated surfaces and HFST sites, using a continuous fixed-slip friction tester. Pavement rutting and macrotexture were also measured. The authors found strong evidence that the HFST surfaces have statistically significant higher friction numbers and surface macro-texture MPD values. The study utilized a 3D laser imaging-based PaveVision3D Ultra technology for surface characterization and evaluation. A multivariate analysis was performed to investigate the effects on HFST performance. The five independent factors were precipitation, average temperature, installation age, type of aggregate, and annual average daily traffic. HFST was found to lose its effectiveness after approximately 5 years of service. Calcined bauxite was found to have the highest surface friction when compared to HFST sites using flints. The study developed a regression model to predict friction and determine the service life of HFST sites. The study found the service life to be approximately 5 years.

Yang et al. (2019) investigated the polishing behavior of various grades of calcined bauxite aggregate. Due to lack of description of the variability in performance of different grades of calcined bauxite, this study was done to better understand the long-term polishing behavior of several HFST aggregates. Hardness tests were also conducted on the aggregate samples to investigate the micro hardness of the samples. High grade calcined bauxite is expensive and causes excessive tire wear. The authors tested 6 alternative grades of calcined bauxite and compared the results obtained for limestone and basalt. The polished stone value (PSV) was determined for each specimen and the surface roughness was measured. Higher PSV values correspond to higher skid resistance and better performance in HFST. The surface profile roughness of the aggregate samples was then investigated using a 3D color laser microscope system.

The results showed that higher grades of calcined bauxite had a higher polished stone value and ranked better than the limestone and basalt aggregates. According to the authors, the PSV values of aggregate after polishing using the standard time were ranked as follows: 90# calcined bauxite > 85# calcined bauxite > 80# calcined bauxite > 75# calcined bauxite > Basalt > 70# calcined bauxite > limestone > 65# calcined bauxite. Based on the PSV results of different grades, a decrease in the alumina content caused a decrease in PSV. The higher grades of calcined bauxite had a higher alumina content and resulted in a higher PSV, relative to the other aggregate samples. Basalt did not pass the minimum requirement for an ultra-thin friction course after an extended polishing time. Limestone was found to have the largest reduction in PSV, and therefore, not suitable for pavement undergoing heavier traffic. 80# calcined bauxite and higher passed the Chinese requirement for use in an ultra-thin friction course. The mineral components of the aggregates with higher Mohs hardness ranges resulted in higher Vickers hardness results for the aggregates. Mineral components of calcined bauxite are mainly corundum and mullite, which have a higher microhardness than the mineral components of basalt and limestone. Smaller porosity of the aggregate was found to result in better cohesion of the mineral components, resulting in higher hardness values for the aggregate. Higher hardness was found to be the main reason for better long-term skid resistance of higher-grade calcined bauxite compared to the other aggregates tested.

In a study performed by Heitzman et al. (2015), at the National Center for Asphalt Technology (NCAT), the authors examined the performance of seven aggregates used in high friction surface treatment systems. The results were compared with the performance of calcined bauxite. The aggregates examined were granite, flint, basalt, silica sand, steel slag, emery, and taconite. The study was divided into three components. The first component was a laboratory evaluation to determine if aggregates from sources in the US provided adequate friction performance for HFST systems. Using the NCAT Three Wheel Polishing Device (TWPD), friction performance of the alternative aggregates was measured. The friction performance results were comparable with the friction performance of calcined bauxite.

The surface texture and friction were also measured by the Circular Texture Meter (CTM) and Dynamic Friction Tester (DFT) in accordance with ASTM test methods E2157 and E1911, respectively. CTM results show that TWPD conditioning for the first 70k cycles resulted in a 20-30% loss in surface texture for all eight aggregates. There was almost no change in surface texture from 70k to 140k cycles of TWPD. DFT results show a friction loss of 11% for the bauxite and over 20% loss for the seven aggregates in the first 70k cycles of TWPD. After 70k cycles of TWPD, six of the aggregates had an additional friction loss with the smallest loss of 4% for granite and largest loss of 12% for basalt.

All tested HFST systems, except the one utilizing slag, maintained surface macro-texture greater than or equal to 1.4mm. All eight HFST systems are expected to provide significant reduction in hydroplaning of vehicle tires. The second component of the study was a field test of each aggregate HFST system using the two research cycles on the NCAT Pavement Test Track. The same two-part polymer bonding agent was used for all aggregates. The sections underwent controlled traffic conditions and CTM and DFT measurements were taken. The bauxite had the highest initial surface friction value with taconite having the second highest. Most of the HFST test sections maintained their relative ranking of surface friction throughout the test, with bauxite and taconite having the highest DFT values.

The third component was a detailed laboratory evaluation of bauxite, slag, taconite, and flint aggregates. The British Pendulum (BP) test and Aggregate Image Measurement Systems (AIMS) with Micro-Deval conditioning were used to examine the surface friction and particle angularity and shape. CTM and DFT results were consistent with the results from the first component. The Micro-Deval test ranks bauxite as best and taconite as lowest performers for aggregate mass loss, however none of the aggregates reached terminal mass loss. AIMS results showed that taconite and bauxite particles were more cubical while flint and slag particles were more elongated. No correlation was found between particle shape and angularity and friction.

In a report by Anderson, et al. (2017) from Washington State Department of Transportation, the authors investigated the results of the installation of Tyregrip® on a ramp prone to run-off-road crashes. Tyregrip® is composed of a two-part epoxy-based binder and covered with calcined bauxite aggregate. The aggregate is 100% fractured and has a nominal size of 2mm. The resin is applied by a vehicle with two feeder tanks that mix the two parts of the epoxy and pump the resulting resin to the spreader bar, spreading the epoxy uniformly onto the pavement. A spreader box drops the calcined bauxite aggregate onto the resin. Friction tests of the first application of the Tyregrip® yielded an average result of 54.1, compared to an average result of 44.1 on road sections directly before and after the road section with Tyregrip® applied. Due to the less than desired increase in friction numbers, the supplier requested a second application of Tyregrip®. The friction results after the second application yielded an average of 76.7, compared to an average of 44.5 on the untreated road sections before and after the section with Tyregrip®. The cost of the treatment was determined to be $36.50 per square yard, found to be considerably higher than the Italgrip® system used in Wisconsin. A second application was needed to achieve the friction results as promised by the supplier of Tyregrip®. The ineffectiveness of the first application could be caused by inexperienced application personnel. The treated section was tested according to ASTM E274-06 and ASTM E501-94 standards once per year for the 5-year service life. The results were found to be exceptionally high with an initial reading of 76.7 in 2011 and a final reading of

73.9 in 2016. Cracking and delamination began occurring two years after installation, in 2013, and continued throughout the service life. The problems may have been caused by the poor condition of the underlying pavement of the treated section. They could also have been caused by contamination of the HFST with deleterious materials, insufficient bond between the epoxy resin and underlying pavement, or a shallow substrate failure of the hot mix asphalt by the HFST. Crash statistics showed a 79% reduction in run-off-road crashes during wet weather from before the application of Tyregrip® and after the application. Tyregrip® was found to be a viable solution for roadways with high rates of run-off-road crashes caused by wet weather.

In a report prepared for Wisconsin Department of Transportation, Bischoff (2008) investigated the results of installing Italgrip™ product at five locations in Wisconsin, on road sections with histories of high accident rates due to wet pavement surfaces. All five road sections tested were concrete pavements. Italgrip™ consists of a two-part polymer resin and steel slag aggregate. The polymer resin was sprayed onto the pavement using a specialized spray truck. The steel slag was applied immediately after using a typical chip spreader. The minimum cure period varied from three to ten hours, depending on temperature. The overall performance of the treatment was evaluated based on five parameters: freeze-thaw, friction, accident analysis, noise, and surface loss. Freeze-thaw testing was conducted in accordance with ASTM C 666. The testing was conducted on concrete and HMA samples in the WisDOT Truax Center Lab.

Testing showed an average mass loss of 1.6 percent for Italgrip ™ on concrete samples, and an average mass loss of 3.3 percent for Italgrip™ on HMA samples. The results were within the acceptable limit of 10 percent mass loss. Friction testing was conducted in accordance with ASTM E 274. The test showed that prior to installation, the average friction number of the sites was 42.9. After installation of Italgrip™, the average friction number rose to 72.6. After two years, the average friction number decreased to 58.3. Five years after installation, the average friction number was 59.4. Accident analysis showed a decrease from an average of 12.9 accidents per year to an average of 5.3 accidents per year after the installation of Italgrip™. Noise measurements showed a decrease of 4 decibels after the installation of Italgrip™ on ground concrete with diamond grinding operation. Surface loss was highest in La Crosse County bridge sites, due to more lateral stresses and higher traffic volume. Surface loss for La Crosse County bridge sites was on average 23 percent. The Italgrip™ System in this study had a reduced cost of $13 per square yard. The current cost of Italgrip™ is about $20 per square yard. Italgrip™ was found to be a viable option for HFST in Wisconsin and was recommended to be approved for use on road sections with high accident rates to due factors impacting pavement friction.

In a recent research effort performed by Chen et al. (2019), the authors investigated the performance of a low-cost HFST, utilizing a waterborne epoxy resin and emulsified asphalt used with fine corundum sand. The aggregate median size of the HFST system was 0.5mm but could be scaled up to 3mm for certain HFST applications. The study focused on skid resistance, durability against freeze-thaw cycles, and reduction of crack propagation. The results were compared with results from HFST systems consisting of epoxy resin with copper slag and two different bauxites with epoxy resin. The gradation of the corundum sand was much finer than the aggregates used in the United States for HFST systems. Skid resistance tests were conducted using the British Pendulum Tester in accordance with ASTM E303, with slight modifications. Untreated samples had a BPN of 60. Samples treated with copper slag yielded the lowest increase in skid resistance, while samples treated with the corundum sand HFST and the bauxites HFST had higher but similar increases. Freeze-thaw cycle testing showed that the new HFST system with corundum sand had a lower durability against moisture, relative to HFST using bauxites. The new HFST still met the minimum BPN value for skid resistance after freeze-thaw testing. This result is attributed to loss of aggregate during sweep testing. Semi-circular bending (SCB) tests showed that all tested HFST systems were able to reduce crack propagation. Crack propagation was delayed by the new system due to adhesive properties and redistribution of loading stress, whereas traditional HFST systems reduced crack propagation due to the extra energy needed to crack the bridge between two sides of the base of the sample. The results from testing the HFST system utilizing waterborne epoxy resin and fine corundum sand were found positive and the new system was found to be a viable option for HFST.

In an investigation performed by Guan et al. (2018), the authors analyzed the skid resistance of four types of aggregates and evaluated the effects of macrotexture and microtexture on skid resistance. Tests on fractal dimension, root mean square height, and Polished Stone Value (PSV) were conducted. The aggregates tested were bauxite (calcined to 1600°C), granite, limestone, and basalt. All four aggregates exhibited the same trend of development of PSV, divided into 3 stages of an accelerated attenuation stage, decelerated attenuation stage, and a stabilization stage. The PSV of bauxite was initially at 52 and it remained at a relatively high level throughout the test. Granite ranked second and basalt ranked third. Limestone ranked last. The results of the PSV test showed that bauxite was the most suitable aggregate for skid resistance. The fractal dimension and root mean square height tests showed that prior to the stabilization rate of PSV development, macrotexture plays the major role in skid resistance. After the critical point at which PSV development enters the stabilization rate, microtexture plays the major role in skid resistance. The root mean square height was found to be a suitable indicator to evaluate long-term skid resistance of the aggregates. Overall results showed that calcined bauxite exhibited the highest skid resistance during long-term polishing and was the most suitable for wearing courses.

In a research effort by Li et al. (2019), the authors investigated the durability and friction performance of single and double layer HFST systems with two gradations of calcined bauxite aggregates. The HFST system in the study was an epoxy-resin binder system of Type III, with calcined bauxite aggregate. Laboratory accelerated polishing was conducted on an HFST system using No. 4 (4.75mm) calcined bauxite aggregate and an HFST system using No. 6 (3.35mm) calcined bauxite aggregate. The HFST system using the coarser No. 4 calcined bauxite aggregate was anticipated to provide better friction performance relative to the HFST system using No. 6 calcined bauxite aggregate. Test slabs of both systems were polished using a three-wheel circular track polishing machine. Surface friction and texture measurements were taken prior to polishing and after reaching a terminal polishing condition. The measurements were taken in accordance with ASTM E1911 and ASTM E2157. Terminal polishing condition was reached quicker when using No. 4 calcined bauxite aggregate, raising concerns about tire damage. No visible loss of aggregate occurred on any of the test slabs. The average mean profile depth (MPD) of the No. 4 calcined bauxite test slabs decreased from 2.27mm to 1.86mm. The average MPD of the No. 6 calcined bauxite test decreased from 1.97mm to 1.53mm. Differences in the Dynamic Friction

Tester (DFT) surface friction of the two candidate systems were found to be negligible. The HFST system using No. 4 calcined bauxite aggregate did not produce greater surface friction than the system using No. 6 calcined bauxite aggregate. Due to concerns related to excessive tire damage caused by No. 4 calcined bauxite aggregate, field evaluation was done using only No. 6 calcined bauxite aggregate. Double- and single-layer test strips were used. The DFT friction coefficient of the double layer test strips was slightly less than that of single layer test strips. This indicated that double layer HFST did not outperform the single layer HFST in terms of surface friction. The friction under actual traffic polishing decreased quicker than under laboratory conditions. The authors concluded that MPD can be used as an accurate frictional metric for quality assurance of the HFST system.

In an older study, Dahir (1979) investigated the various properties of aggregates that affect the skid and wear resistance of aggregates. Particle size is important for adequate water escape channels, sideway force coefficient of friction, and skid resistance. Based on literature findings on optimum aggregate size for optimum surface performance, the authors recommended using coarse aggregate size in the range of 3 to 12mm. Particle shape is important for increased shear strength of bituminous mixture, improved wet skid resistance, and development of high contact pressure points to break water film between pavement surface and tires. Angular aggregate particles are preferred over rounded particles. Aggregate gradation is important to achieve a variety of effects. For example, dense gradings allow for high impermeability and stability. Open gradings allow for fast drainage of wet pavement at tire contact area. Fine gradings are used when pavement is exposed to low to moderate speed and traffic volume. One-size gradings are used to maintain resistance to abrasion and skidding and are used in surface treatments. Aggregate resistance to polishing and wear is caused by mechanism involving abrasion of small aggregate asperities. All aggregate properties affect resistance to polishing and wear, particularly aggregate petrography. Petrography involves an aggregate's constituent mineral proportion and hardness, grain consolidation, and differential wear. High hardness with high consolidation improves aggregate wear resistance. Medium to coarse grains with sharp edges and protrusions create more angular particles, improving the frictional and wear resistance. Grains cemented by a softer matrix allow for a faster wear and surface renewal, resulting in increased long-term surface resistance to polishing, but causing more rapid surface aggregate loss. Mineral composition and differential hardness have the utmost importance in long-term frictional resistance. Higher differential hardness produces more long-term friction level. Calcined bauxite is composed of corundum crystals in a glassy matrix and has a crystal hardness level of H = 9 and matrix hardness of H = 6. Aggregate, consisting of crystals with high toughness and hardness in a matrix with relatively lower hardness, will have a high level of polishing and wear resistance through slow differential wear and irregular grain fracture. Small, well-distributed voids between the crystals, also improve polishing and wear resistance, as evident in calcined bauxite and air-cooled blast-furnace slag.

Zanko et al. (2003) investigated the physical, geological, mineralogical, and chemical properties of a crushed taconite mining byproduct: tailings. Taconite tailing samples were taken from five locations in the westernmost operations on the Iron Range. Taconite tailings are highly siliceous with a low magnetic iron content compared to the crude ore from which they are generated, and range in size from fine to coarse. Fine tailings are composed of very fine rock particles. More than 90% of the aggregate particles are smaller than 0.003 in, much too fine for aggregate use. Coarse tailings are very angular, and the aggregate particles are typically finer than 3/8 in. Taconite tailings are generated in large quantities and, where available in excess, require very little additional processing to produce suitable products. Aggregate testing showed that taconite tailings had desirable characteristics for use in bituminous, base, and fill applications. The Fine Aggregate Angularity (FAA) test showed that the average of each taconite company met the Superpave minimum of 45 percent and had acceptable FAA values. The coarse taconite tailings easily passed the sand equivalent (SE) minimum which identifies the presence of clay in the aggregate. No lightweight particles were detected in the samples. Hydraulic conductivity and R-value tests showed that the taconite tailings behave as fine-draining sand. This result seems to make the tailings a good choice for granular fill/base material to minimize freezing effects. Specialized microscopy was conducted using X-ray diffraction, polarized light microscopy (PLM), scanning electron microscopy (SEM), and transmission electron microscopy (TEM) to determine shape and size of the minerals in the tailings. Specialized microscopy results showed that most of the coarse tailings are composed primarily of quartz and are hard and resistant to abrasion. No asbestos or amphibole minerals were present in the tailings.

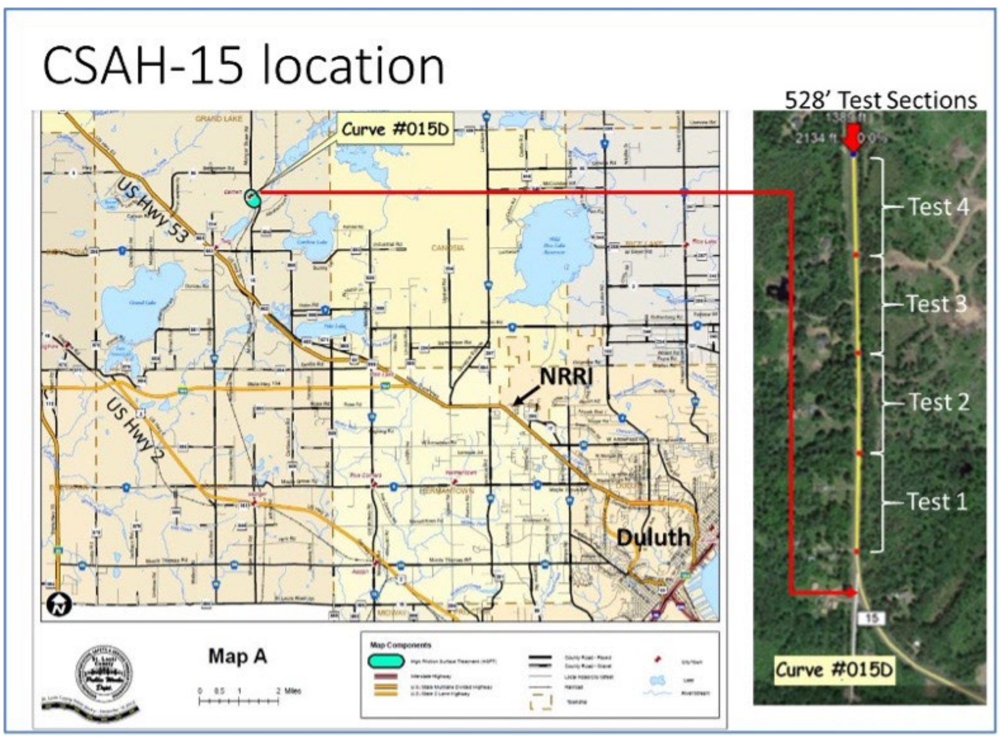
For the current project, the project team is referencing St. Louis County's Summer of 2020 HFST installation program (Appendix B). The pertinent HFST information is presented on the following pages, extracted from a document provided by St. Louis County Traffic Engineer, Victor Lund.

Chapter 3: Identification of HFST Contractor, and Acquiring Materials

3.1 Project Test Location Selection

The project's test location is CSAH-15 (Munger Shaw Road) in St. Louis County, just northwest of Duluth and the NRRI, near US Hwy 53 (Figure 3.1). This location was selected prior to the official project start date. It was originally planned to be comprised of four test sections, each 528 feet (1/10th of a mile) in length and 11 feet in width, or 645 yd^2 per section. The test sections were to be installed along the straightaway northbound lane of CSAH-15, just past the horizontal curve (Curve #015D) that received a calcined bauxite surface treatment in late July of 2020 as part of St. Louis County's horizontal curve high friction surface treatment program.

Figure 3.1. Project location map showing proposed test sections



The calcined bauxite treatment is the lighter-colored pavement (relative to the existing darker-colored pavement) in the foreground of the photograph (Figure 3.2). The view is looking north. The effect that aggregates and pavement surface treatment color has on pavement temperature were to be measured and documented using thermal imaging. Figure 3.3 is a close-up view of the existing pavement (left) and the calcined bauxite treatment (right). Note the finer size of the calcined bauxite aggregate, which reflects the specified HFST gradation.

Figure 3.2. Calcined bauxite surface treatment (foreground) and existing pavement at CSAH-15 location (looking north): November 2, 2020

Figure 3.3. Closeup of existing pavement (left) and calcined bauxite treatment (right)

To reiterate, the test sections were originally planned to consist of the following:

- Bauxite applied with epoxy/resin (Test 1)
- Taconite applied with epoxy/resin (Test 2)
- Taconite applied with MnDOT's specified micro surfacing polymerized AC binder (similar to seal coat) (Test 3)
- A taconite/bauxite 50/50 blend applied with an asphalt binder (Test 4a); or a micro surfacing 50/50 blend of taconite/bauxite (Test 4b)

The existing chip sealed asphalt pavement and the newly installed HFST at Curve #015D would as controls. As originally conceived, St. Louis County had planned to micro mill the existing pavement to prepare the four test sections for their respective surface treatments.

NOTE: *The possibility of adding one or two more micro-surfacing type test sections was raised by the project TL during an October 2020 discussion. This possibility was reviewed with St. Louis County during a follow-up meeting .*

3.2 Identification of Potential HFST Contractors

Following consultation with St. Louis County Traffic Engineer Vic Lund and the project TL, Tracey Von Bargen, the PI contacted five potential contractors to request cost quotations/bids (including mobilization, traffic control, and demobilization) for the HFST and micro surfacing installations. As reported in the project's Task 1 report, it had been hoped the installations could take place in August or by early September of 2020, but the following complicating factors led to the postponement of the installations until 2021:

1) The construction season was already well underway, and most of the contractors had existing project commitments until Labor Day;
2) The mix design for the taconite-based micro surfacing applications was requiring additional time to develop;
3) The risk of experiencing sub-optimal weather and pavement temperature conditions increased as the season advanced, which could compromise the quality of the installations; and
4) Micro milling the existing pavement prior to securing the pavement surface treatment installation contract(s) was risky from a safety perspective, especially so late in the season.

Based on these factors, it was agreed that:

- The installations should not be rushed
- June of 2021 be targeted for the installations, and
- The coming winter (2020/2021) would be the best time to re-submit bid requests to contractors, thereby increasing the likelihood of receiving multiple bids and securing a definite installation date window.

Furthermore, the fall 2020 and winter 2021 months would provide the additional time still needed for developing and finalizing the micro surfacing mix design. And lastly, a June 2021 installation target date would provide better ambient temperature conditions, maximum pavement solar heating gain, and maximum daylight (working) hours. Importantly, this would also allow the entire test section location to be micro milled during a single mobilization (saving cost) and minimize the length of time between micro milling and the surface treatment installations.

As described in Task 1, the necessity to postpone the test section installation until June of 2021 meant that measuring and assessing the effect of winter 2020-2021 snow plowing was not possible during the project's first year. The PI therefore recommended that the project's December 31, 2023, end date be extended to June 30, 2024, to allow for the collection of data that reflects three years of snow plowing impacts instead of only two years. With a 6-month extension, the project would then have three full years of summer and winter pavement condition measurements and assessments to report **(NOTE: the project's end date was later extended to June 30, 2025).**

3.3 Material Acquisition

Acquisition of bulk quantities of materials for the test installations took place in 2021, following the selection of contractors. As described previously, the taconite mining byproduct derived HFST (and micro surfacing-type) aggregate were to be donated. Prior to the bulk donation of aggregate, the PI requested and received representative samples of calcined bauxite and taconite HFST aggregate in 2020. The acquired aggregate materials allowed preliminary characterization work and test specimen fabrication and laboratory testing to take place prior to test section installation. This meant preliminary dynamic friction tester (DFT) and British Pendulum assessments could be done during the fall of 2020 and/or spring of 2021, to get a sense of what baseline friction numbers would be for the existing pavement and the recent (2020) HFST installation, within and outside the wheel paths. These assessments were coordinated with the project's co-investigators at UMD and UMTC, with MnDOT, and with St. Louis County.

A change in the gradation of the source taconite mining byproduct material (tailings) to be used for the project's micro surfacing-type applications complicated timely completion of the micro surfacing mix design originally anticipated for use on the project. Therefore, an alternative surface treatment approach was discussed and ultimately chosen for installation in 2021. This alternative is described in Chapter 5.

Chapter 4: Laboratory Testing of Materials

4.1 Introduction

In this chapter, the research team conducted: a) initial laboratory and field friction testing of representative samples of calcined bauxite and taconite high friction surface treatment (HFST) aggregate; and b) mineralogical, chemical, and microscopic characterization of the two aggregate types. These assessments were coordinated with the project's co-investigators at UMD and UMTC, St. Louis County, and NRRI personnel. These activities were designed to provide baseline (pre-wear) information against which similar testing conducted throughout the remainder of the project could be compared.

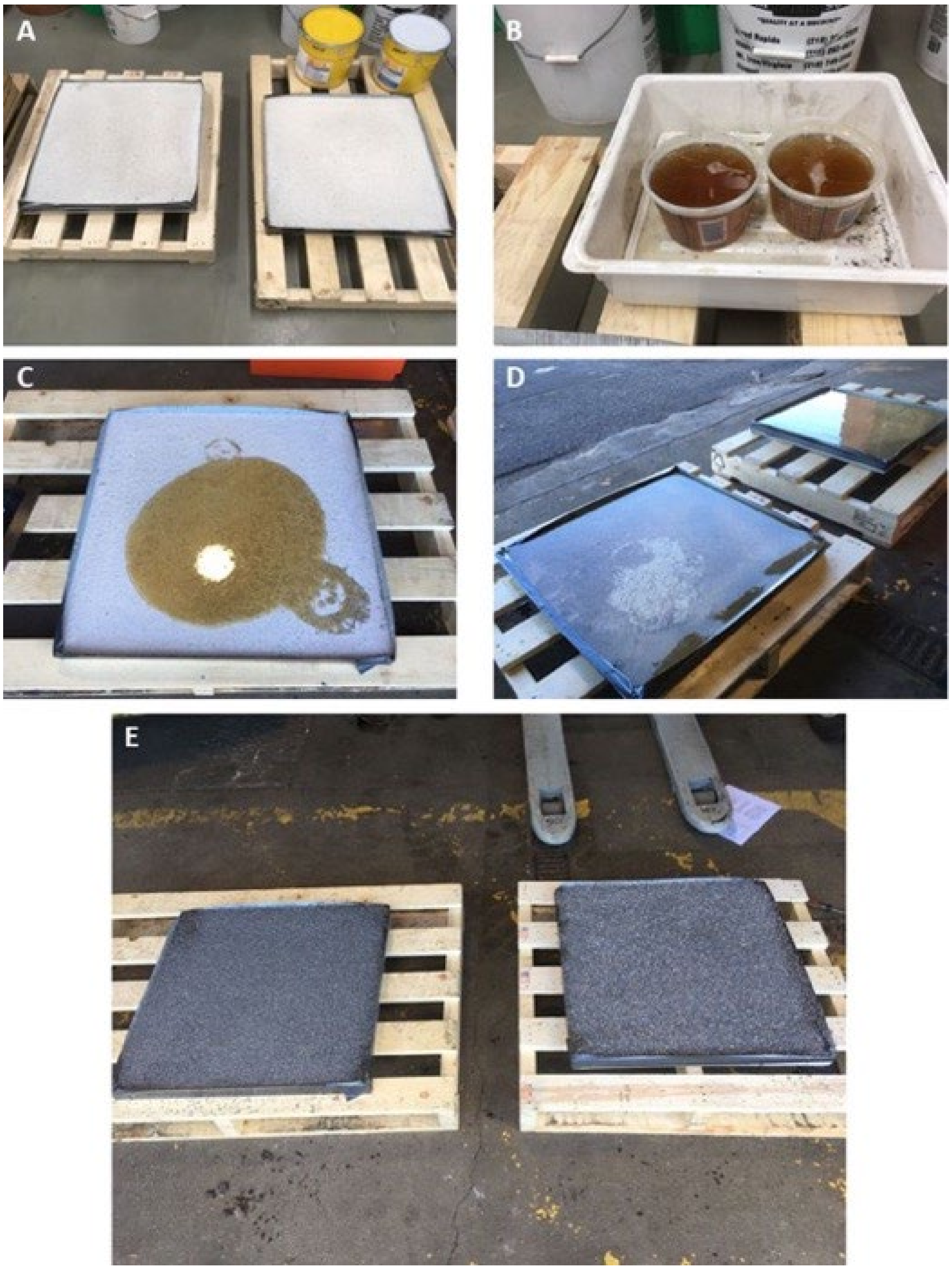
In preparation for these 4 activities, the PI was in communication with the project's Project Coordinators (PC) David Glyer and Brent Rusco; Technical Liaison (TL) Tracey Von Bargen (Grant County); and St. Louis County Traffic Engineer and project Technical Advisory Panel (TAP) member, Victor Lund; as well as the project's co-Investigators, Professors Mihai Marasteanu (UMTC) and Manik Barman (UMD).

4.2 Friction testing of laboratory prepared specimens

4.2.1 Test specimen/slab preparation

Laboratory-scale specimens were prepared at the NRRI to simulate the epoxy/resin-based surface treatments to be installed at the project's field test site. Two 23.5" x 23.5" (60cm x 60cm) concrete pavers/slabs were used as a simulated pavement surface to which quantities of epoxy/resin and HFST aggregates were applied, per the application rate specifications established for HFST applications. According to the HFST contractor, the recommended resin application rate achieves coverage of 25 to 32 ft^2 per gallon and a thickness of 60 mils, and aggregate is applied at 12-15 lb/yd^2. A 1:1 two-part resin product (Sikadur®-22 Lo-Mod) provided by Sika Corporation to the NRRI in January 2021 was used (see HFST product information sheets in Appendix C, topped with the project's taconite and calcined bauxite HFST aggregates (Figure 4.1).

Figure 4.1. Laboratory-scale specimens to simulate the epoxy/resin-based surface treatments: A) 23.5" x 23.5" (60cm x 60cm) concrete pavers/slabs used to simulate pavement; B) resins mixed at appropriate volume to match specification requirement for treated pavement (and specimen) surface area; C) resin applied to specimen; D) specimens completely covered with resin and ready to receive aggregate; E) HFST aggregates applied to both specimens (taconite left; calcined bauxite right)



4.2.2 Dynamic Friction Tester (specimen testing)

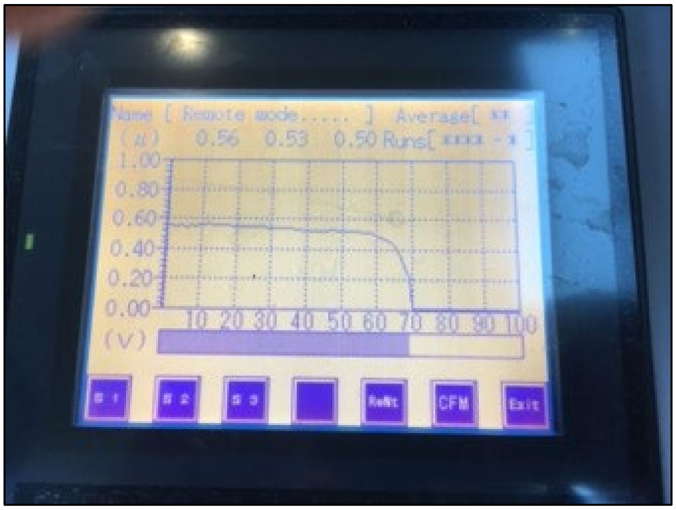
The as-prepared specimens were of sufficient size to test the Dynamic Friction Tester (DFT). A description of the DFT and its measurement principles are provided by the manufacturer, Nippo Sangyo Co., LTD, at the following link: http://www.nippou.com/en/products/dft.html

The DFT – on loan from MnDOT to the University of Minnesota's Department of Civil, Environmental, and Geo-Engineering (CEGE) – was brought to the NRRI by Mugurel Turos on the morning of June 16, 2021. The testing was conducted to confirm the DFT's operating parameters, data acquisition, and data transfer prior to its use at the project test site later that afternoon and for subsequent project testing. Figure 4.2 shows the setup in the NRRI's rear parking lot.

Figure 4.2. Dynamic friction tester (DFT) evaluation of simulated pavement specimens at the NRRI on June 16, 2021. Setup shows DFT, water supply hose, data interface and acquisition laptop on cart, and 12V battery for power

When the DFT reaches the target speed (velocity), its rotating disk/platen drops, and the affixed rubber pads engage with the pavement surface to simulate braking/skidding. An example of how velocity and the friction value (μ) are plotted and recorded is shown in Figure 4.3.

Figure 4.3. DFT data as displayed on the laptop screen. Velocity (in km/h) is shown on the x-axis, and friction (µ) is shown on the y-axis

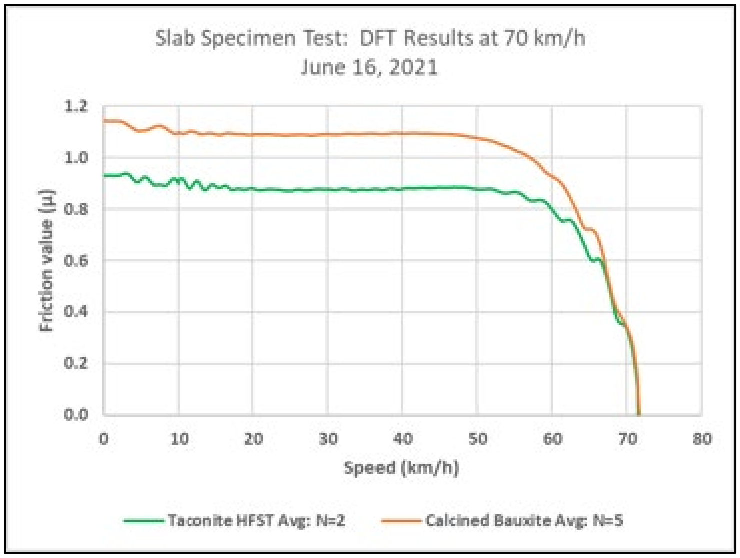


The DFT is operated under simulated wet pavement conditions, with water supplied to the DFT and pavement from an elevated stainless-steel tank. Initial testing at the NRRI began with the DFT's speed set at 80 kilometers per hour (50 mph), using the taconite HFST specimen slab. After four runs, it became apparent that the 80 km/h setting drew too much power from the stand-alone 12V battery powering the DFT to reach the targeted speed in a timely manner. Therefore, the remaining DFT testing was conducted at a 70 km/h (43.5 mph) setting.

DFT tests were run on the two pavement specimens to establish baseline laboratory friction values for both aggregate types: two for the taconite slab and five for the calcined bauxite slab. These baseline values will be available for comparison to additional lab specimens and the installed pavement sections that have been subjected to wear. The rubber pads were replaced with the taconite and calcined bauxite tests. The results are presented in Figure 4.4.

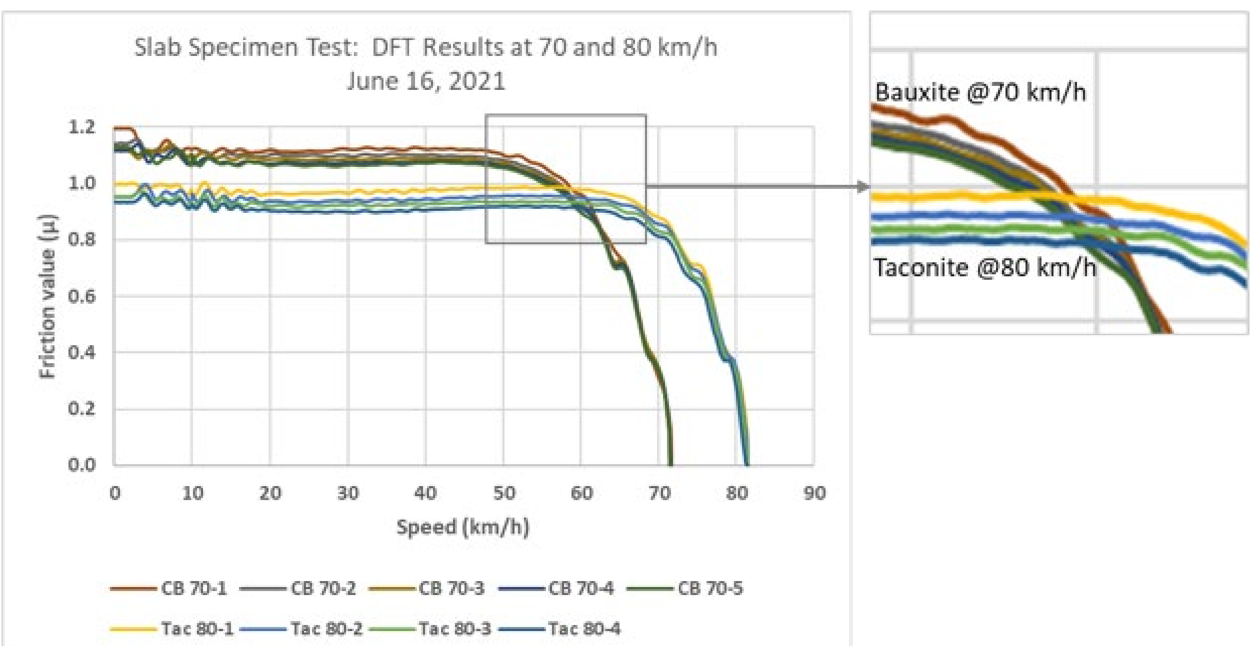
This figure is the DFT results of taconite HFST specimen and specimen with calcined bauxite treatment when the testing speed is 70km/h. In general, specimen with calcined bauxite treatment presents higher friction value.

Figure 4.4. DFT test results for HFST specimen slabs: taconite and calcined bauxite treatments



The 80 km/h tests run on the taconite HFST specimen slab showed a trend of decreasing friction values with each successive test. A similar trend occurred with the tests run on the calcined bauxite HFST specimen slab at 70 km/h, as Figure 4.5 and the inset illustrate. The trend could be due to increasing abrasion (wear) of the DFT's rubber pads and/or a buildup of abraded pad rubber on the specimen.

Figure 4.5. Individual DFT slab specimen results for calcined bauxite at 70 km/h and taconite at 80 km/h (inset shows trends)

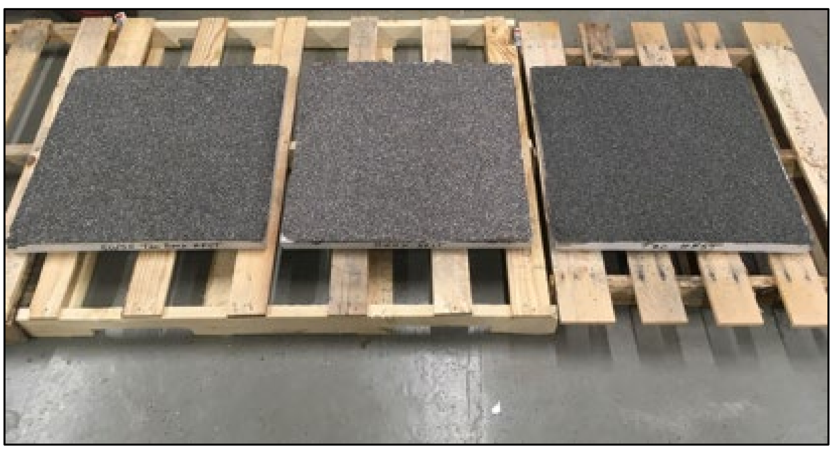


Considering this trend and the potential reasons for it, the investigators agreed that for all future tests the DFT should be moved between runs to avoid repeated operation over the same circular path.

Three more HFST specimen slabs (100% taconite, 100% bauxite, and a 50:50 blend) were similarly prepared at the NRRI on August 22 (Figure 4.6) and shipped to the North Central Superpave Center (NCSC) at Purdue for accelerated wear testing using its Circular Track Polishing Machine (CTPM).

The project team originally expected to purchase this equipment, but co-investigator Mihai Marasteanu contacted Ayesha Shah at the NCSC, and the NCSC conducted the testing instead. As described in the project work plan, the slabs were to be polished in a CTPM developed at NCAT (Kowalski et al., 2010) to simulate the effects of traffic. The surface texture and friction of the slabs are measured before and periodically during the polishing process using a Circular Track Meter (CTM) (American Society for Testing and Materials (ASTM) E2157-15, "Standard Test Method for Measuring Pavement Macrotexture Using the Circular Track Meter") and Dynamic Friction Tester (DFT) (ASTM E1911-09, "Standard Test Method for Measuring Paved Surface Frictional Properties Using the Dynamic Friction Tester"). The CTM and DFT measurements are then used to determine the International Friction Index (IFI) for each specimen. The tests were to take approximately 2-3 weeks to complete.

Figure 4.6. HFST specimen slabs for Circular Track Polishing Machine (CTPM) testing at the North Central Superpave Center - 50:50 blend of taconite and calcined bauxite (left); 100% calcined bauxite (center); and 100% taconite (right)



On September 7, 2021, the HFST-treated slabs were delivered to the NCSC for accelerated wear testing using its CTPM. The CTPM simulated the effects of traffic moving over a surface by subjecting the test specimens to the equivalent of 300K wheel-passes (Figure 4.7). Surface texture was also measured using a laser-based CTM, with the texture reported in terms of the Mean Profile Depth (MPD) in millimeters. NCSC's 2021 lab-based findings were provided in a report by A. Shah, which is included in Appendix D, a reference against which the results of the project's subsequent field-based friction testing presented in Chapter 7 could be compared.

Figure 4.7. DFT20 vs. wheel passes (Source: Shah, 2021)

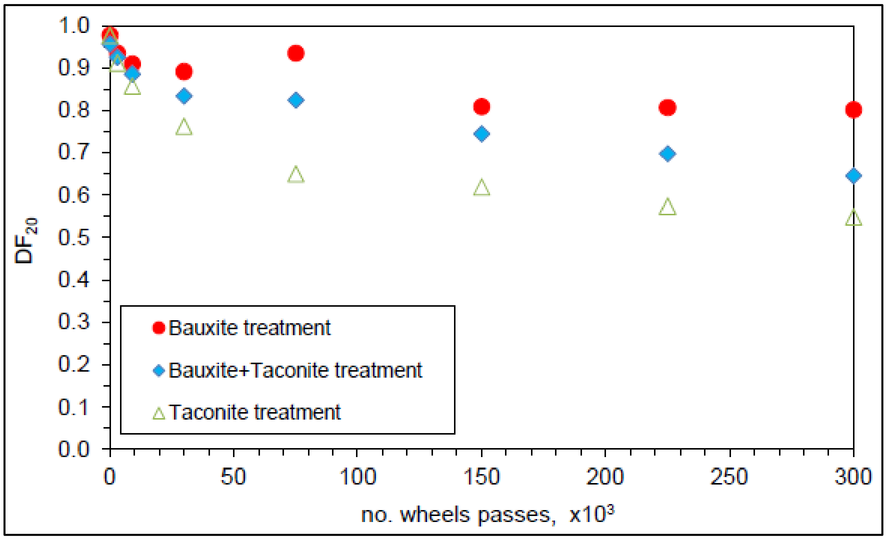


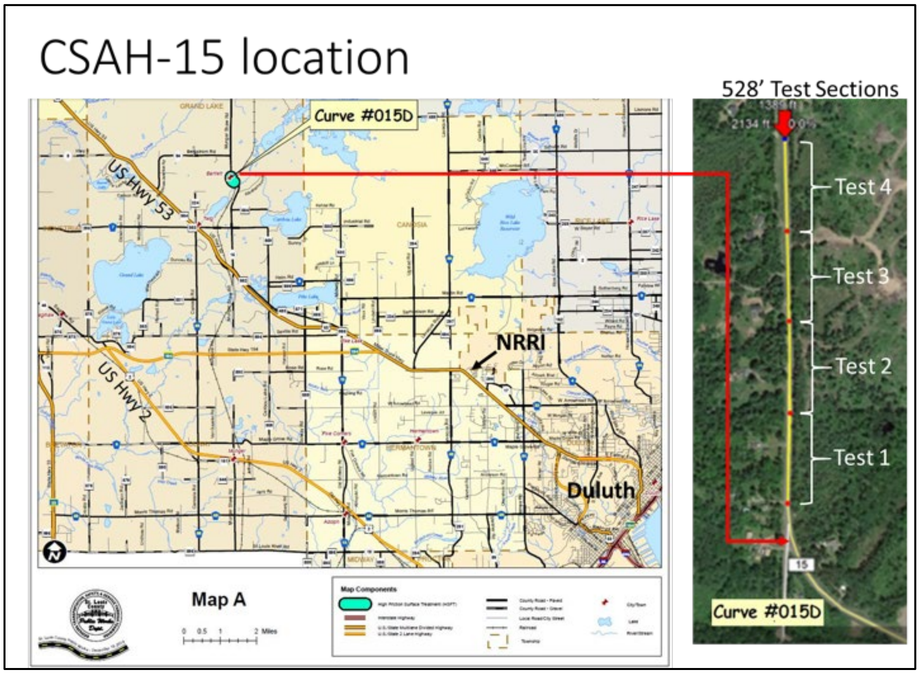
Figure 4.7 shows the difference in friction between the 100% bauxite, 50:50 bauxite/taconite, and 100% taconite treated specimens, as determined by NCSC's testing after 300K wheel passes. The 100% bauxite and 100% taconite friction differential are significantly greater than what the project's field testing has shown through May of 2025 after an estimated 2 million wheel-passes by actual vehicle traffic and four seasons of snow plowing. These finding differences are discussed in greater detail in Chapter 7.

4.3 Friction testing at project test section location

4.3.1 Dynamic Friction Tester (field testing)

To recap, the project's test location is CSAH-15 (Munger Shaw Road) in St. Louis County, just northwest of Duluth and the NRRI, near US Hwy 53 (Figure 4.8). Four test sections, each 528 feet (1/10th of a mile) in length and 11 feet in width, or 645 yd^2 per section, were to be installed along the straightaway northbound lane of CSAH-15, just past the horizontal curve (Curve #015D) that received a calcined bauxite surface treatment in late July of 2020 as part of St. Louis County's horizontal curve high friction surface treatment program.

Figure 4.8. Project location map showing proposed test sections.



Initial friction testing using the DFT and a British Pendulum took place at the project's field test location the afternoon of June 16, 2021 (Figure 4.9). Baseline friction measurements were made of the existing pavement and the recent (2020) calcined bauxite HFST installation, within and between the wheel paths of both pavement surfaces. The June 16 field testing was coordinated with St. Louis County, which provided traffic control support.

The remaining testing included DFT and BP tests every 6 months (in the springtime following winter snow plowing, and in the fall before snow plowing starts) and at least one locked-wheel skid test per year for the duration of the project. Arrangements were also made with MnDOT to employ its "Road Doctor" to test each test section for international roughness index (IRI) surface profiles, use LIDAR and GPS positioning, and generate thermal images.

Figure 4.9. DFT and British Pendulum setup at calcined bauxite surface treatment (foreground) and existing pavement at CSAH-15 location (looking north): June 16, 2021

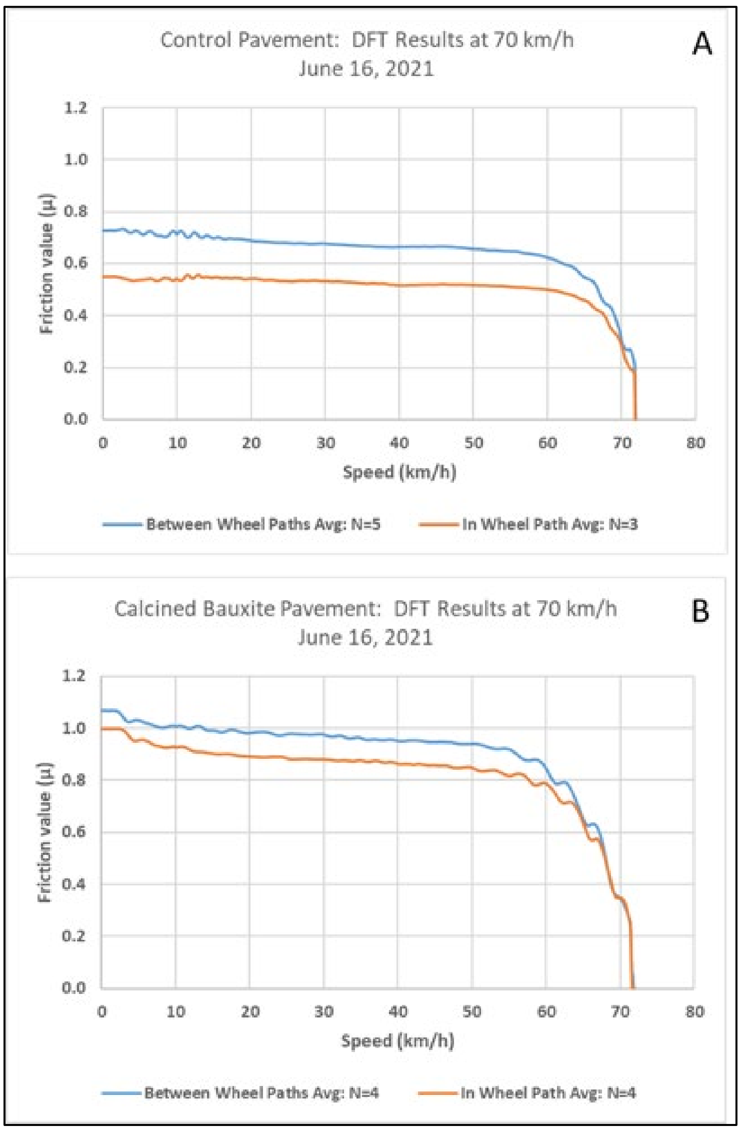
DFT and BP testing took place where the existing pavement and the previously installed (2020) calcined bauxite HFST meet. The southbound lane of CSAH 15 was chosen for running the friction tests because it provided the longest sightline for traffic approaching from the north, which made traffic control safer and more effective.

DFT power was supplied by connecting cables to the battery terminals of the University vehicle. The vehicle was kept running to maintain steady power. The DFT's water supply tank was placed under the open hood of the vehicle (Figure 4.10), to which water was periodically added. Supply water was brought to the project location in a 75-gallon tank filled at the NRRI.

Figure 4.10. DFT setup at the project test location on June 16, 2021, where the light-colored calcined bauxite treatment from 2020 and the darker existing (control) pavement abut. Note St. Louis County traffic control personnel in the background

The DFT was run to simulate a vehicle speed of 70 km/h (43.5 mph), which corresponds closely to the posted speed limit of 45 mph at this location. Subsequent project tests were conducted at 80 km/h, about 5 mph above the posted speed limit (more analogous to the "design speed" of the roadway). Three to five separate runs were made per setup, in and between the wheel paths of both pavements. DFT data were stored on a laptop, compiled, and summarized. Figure 4.11 shows the average baseline DFT data for the four setups (two control (A) and two calcined bauxites (B). The calcined bauxite treatment provides significantly higher friction values. The testing also shows that the friction value is lower within the wheel path than it is between the wheel paths of both pavements, indicating the impact of traffic wear over time along the wheel paths.

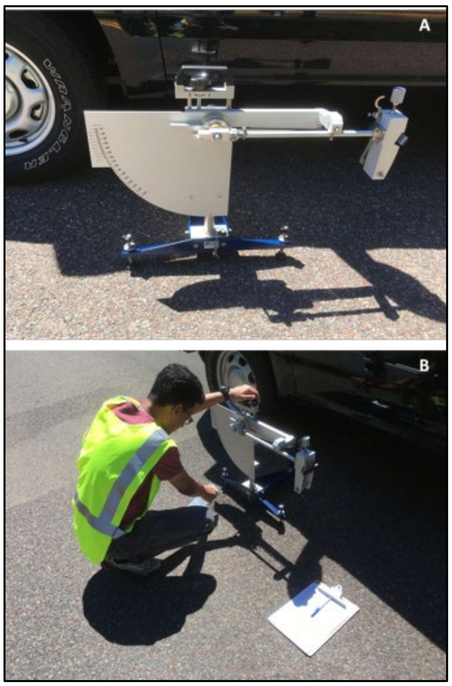
Figure 4.11. DFT field test results at 70 km/h for control and calcined bauxite pavement surfaces



4.3.2 British Pendulum Test

The British Pendulum Test (BPT) Test was conducted for the HFST project to identify the surface frictional properties of the existing and newly constructed portion of an asphalt concrete pavement (Figure 4.12).

Figure 4.12. British Pendulum (A); Testing pavement friction using British Pendulum (B)



The BP test was conducted on June 16, 2021, in accordance with ASTM E303-93 (Reapproved in 2018) and the results of the BP test are discussed in the following Table 4.1 and Table 4.2. The four BP test values taken in each observation were averaged and rounded off to the nearest greater whole number.

Table 4.1. BP test results for the existing asphalt concrete test section

Test Sequence	BP number	Average BP number	Std. Dev. BP number	Surface Temperature	Test Location	Comments
1, 2, 3, 4	57, 55, 55, 56	56	0.8	45° C	Wheel-path	Pendulum swing path parallel to the direction of the traffic (for longitudinal friction)
1, 2, 3, 4	60, 61, 61, 62	61	0.7	45° C	Wheel-path	Pendulum swing path perpendicular to the direction of the traffic (for lateral friction)

Table 4.1 shows the BP numbers for the existing in-service asphalt pavement section. The surface texture observed was micro-texture. The BP number when compared in parallel and perpendicular to the direction of the traffic along the wheel path shows that longitudinal friction is less than lateral friction. Table 4.2 shows the BP values for the newly modified asphalt section with bauxite aggregates.

Table 4.2. BP test results for the newly constructed asphalt concrete test section with bauxite aggregates

Test Sequence	BP number	Average BP number	Std. Dev. BP number	Surface Temperature	Test Location	Comments
1, 2, 3, 4	73, 72, 72, 70	72	1.1	46° C	Wheel-path	Pendulum swing path parallel to the direction of the traffic (for longitudinal friction)
1, 2, 3, 4	83, 85, 83, 84	84	0.8	46° C	Wheel-path	Pendulum swing path perpendicular to the direction of the traffic (for lateral friction)
1, 2, 3, 4	71, 72, 74, 74	73	1.3	47° C	Centerline	Pendulum swing path parallel to the direction of the traffic (for longitudinal friction)
1, 2, 3, 4	85, 85, 84, 86	85	0.7	47° C	Centerline	Pendulum swing path perpendicular to the direction of the traffic (for lateral friction)

The BP numbers indicate that the friction characteristics overall in this section are superior when compared to the existing old asphalt section. Also, the comparison of the BP numbers in the wheel-path and centerline indicates that the wheel path friction to be slightly lower than the centerline friction. This may be because the centerline portion experiences less wear and tear compared to the wheel path. However, the difference is statistically insignificant. As more data is collected during the project, a more robust statistical assessment can be made.

The overall comparison of BP numbers between the existing old asphalt section in Table 4.1 and the modified asphalt section with bauxite aggregates in Table 4.2 shows that the bauxite modified section has far better frictional characteristics compared to the existing old asphalt test section.

Table 4.3 shows that the BP value on the solid white shoulder line of the bauxite modified section is only 46, lesser than any other BP values observed along centerline or wheel path of either pavement. This shoulder line test illustrates how striping/pavement painting reduces the friction characteristics of the surface it is applied to.

Table 4.3. BP test results on the solid white shoulder line for the newly constructed asphalt concrete test section with bauxite aggregates

Test Sequence	BP number	Average BP number	Std. Dev. BP number	Surface Temperature	Test Location	Comments
1, 2, 3, 4	46, 46, 45, 46	46	0.4	47° C	On the solid white shoulder line	Pendulum swing path parallel to the direction of the traffic (for longitudinal friction)

4.4 Characterization testing of aggregate materials

Representative samples of both aggregate materials were acquired in the first quarter of 2021.

Subsamples were provided to the NRRI's Coleraine Labs for mineralogical, chemical, and microscopic characterization.

4.4.1 Mineralogy

The mineral phases present within both aggregates were determined using X-ray diffraction (XRD) analysis. As Table 4.4 shows, the dominant mineral phase present in taconite HFST is quartz (SiO_2), while in calcined bauxite the dominant mineral phase is corundum (Al_2O_3). Quartz has a Mohs hardness of 7, while corundum has a Mohs hardness of 9. The quartz present in taconite HFST is naturally occurring. The corundum present in calcined bauxite HFST is synthetically produced by calcining naturally occurring bauxite – which has a Mohs hardness of 1 to 3 – at temperatures exceeding 1000°C, most often in the 1500°C range. Calcined bauxite aggregate is essentially a high-temperature ceramic product analogous to extremely coarse aluminum oxide sandpaper grit.

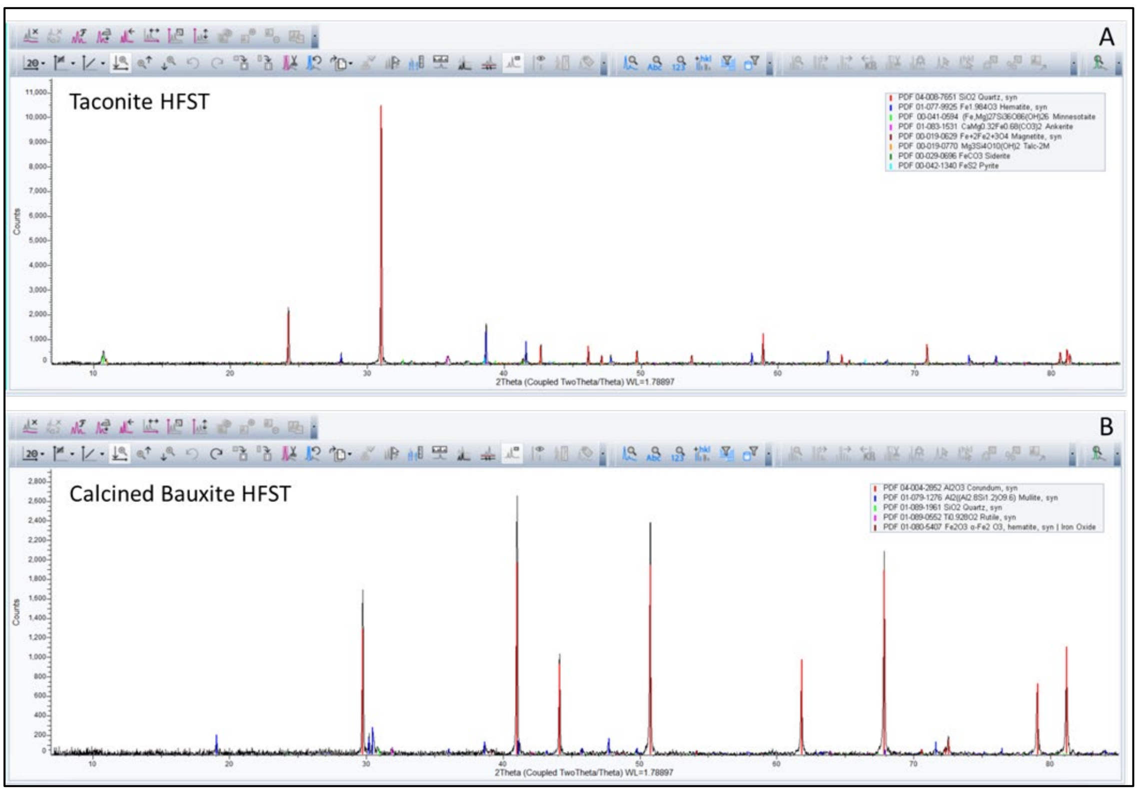
Table 4.4. XRD Final Siroquant Results - Mineral Phase Refinement for Taconite and Calcined Bauxite HFST aggregate

HFST Taconite/Mineral Phases	Weight (%)	Error of Fit
Quartz (SiO_2)	64.0	0.06
Hematite (Fe_2O_3)	18.9	0.02
Ankerite [$Ca(Fe, Mg)(CO_3)_2$]	5.9	0.01
Talc [$Mg_3Si_4O_{10}(OH)_2$]	4.2	0.00
Siderite ($FeCO_3$)	3.5	0.00
Magnetite (Fe_3O_4)	1.7	0.00
Minnesotaite [$Fe_3Si_4O_{10}(OH)_2$]	1.2	0.10
Pyrite (FeS_2)	0.7	0.00

HFST Taconite/Mineral Phases	Weight (%)	Error of Fit
HFST Calcined Bauxite/Mineral Phases	Weight (%)	Error of Fit
Corundum (Al_2O_3)	84.9	0.17
Mullite ($3Al_2O_32SiO_2$)	11.9	0.02
Rutile (TiO_2)	1.5	0.00
Quartz (SiO_2)	0.9	0.00
Hematite (Fe_2O_3)	0.7	0.20

Corresponding XRD traces are present in Figure 4.12, for taconite HFST (A) and calcined bauxite HFST (B). The major peaks represent quartz for taconite and corundum for calcined bauxite.

Figure 4.13. X-ray diffraction traces for taconite (A) and calcined bauxite (B) HFST aggregates.



4.4.2 Chemistry

The chemical composition (major oxide and elemental) of both aggregates was determined using energy dispersive x-ray fluorescence (EDXRF) analysis. The results are summarized in Table 4.5 and Table 4.6, and reflect the mineralogical analyses presented previously. Taconite HFST major oxide chemistry is dominantly SiO_2 and Fe_2O_3 (quartz and hematite) while calcined bauxite HFST is dominantly Al_2O_3 (corundum). Elemental analyses (Table 4.6) are analogous.

Table 4.5. Major oxide chemical analysis of HFST aggregates

Job ID Preparation Evaluation ID Sample ID Experiment name Measurement Finished	1102 Pressed pellet 935 ML21#53 HFST Taconite Oxide SMART-Oxides 6/3/2021 11:35	1104 Pressed pellet 937 ML21#54 HFST Calcined Bauxite Oxide SMART-Oxides 6/3/2021 11:55
Al_2O_3 (%)	1.33	79.59
SiO_2 (%)	68.21	11.92
P_2O_5 (%)	0	0.36
SO_3 (%)	0.11	0.05
Cl (%)	0.01	0
K_2O (%)	0	0.32
CaO (%)	1.59	0.58
TiO_2 (%)	0.04	3.79
V_2O_5 (%)	0.01	0.1
Cr_2O_3 (%)	0.03	0.1
MnO (%)	0.61	0.02
Fe_2O_3 (%)	28.07	2.77
CuO (%)	0	0.01
Ga_2O_3 (%)	0	0.02
SrO (%)	0	0.14
Y_2O_3 (%)	0	0.01
ZrO_2 (%)	0	0.18
Nb_2O_5 (%)	0	0.02
HfO_2 (%)	0	0.01
Sc_2O_3 (%)	0	0
NiO (%)	0	0
ZnO (%)	0	0
Ta_2O_5 (%)	0	0

Table 4.6. Elemental chemical analysis of HFST aggregates

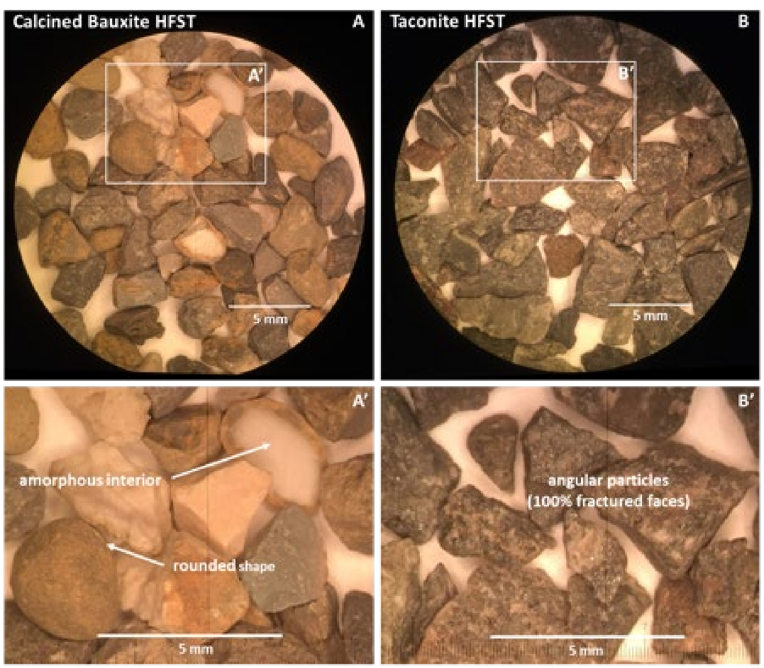
Job ID Preparation Evaluation ID Sample ID Experiment name Measurement Finished	1102 Pressed pellet 935 ML21#53 HFST Taconite Elements SMART-Elements 6/3/2021 11:44	1104 Pressed pellet 937 ML21#54 HFST Calcined Bauxite Elements SMART-Elements 6/3/2021 12:46
Al (%)	1.12	72.49
Si (%)	52.63	12.2
P (%)	0.03	0.29
S (%)	0.08	0.04
Cl (%)	0.02	0
K (%)	0	0.69
Ca (%)	2.13	1.05
Ti (%)	0.04	6.06
V (%)	0	0.17
Cr (%)	0.03	0.19
Mn (%)	0.97	0.06
Fe (%)	42.93	5.68
Cu (%)	0	0.03
Ga (%)	0	0.04
Sr (%)	0	0.39
Y (%)	0	0.04
Zr (%)	0	0.45
Nb (%)	0	0.04
Hf (%)	0	0.02
Sc (%)	0	0.01
Ni (%)	0.02	0.04
Zn (%)	0	0.01
Ta (%)	0	0.01

4.4.3 Microscopy

Subsamples of both HFST aggregates were examined microscopically. Images showing the gross particle size and shape characteristics of both HFST aggregates are shown in Figure 4.14 and Figure 4.15. The inset images of Figure 4.15 provide a more detailed view of the respective morphologies of the calcined bauxite (A’) and taconite aggregate (B’) particles. Note that not all the calcined bauxite particles are angular, and the amorphous, ceramic-like nature of the interior of one of the particles; whereas the taconite particles are uniformly angular (100% fractured faces), and individual mineral grain boundaries are visible.

Figure 4.14. Comparison of calcined bauxite HFST aggregate (left) and taconite HFST aggregate (right)

Figure 4.15. Microscopic images showing size and shape characteristics of calcined bauxite HFST aggregate (A and A') and taconite HFST aggregate (B and B')



Grain mounts were produced for each of the samples – HFST Taconite and the HFST Calcined Bauxite – to characterize the opaque mineral phases (reflective-light microscopy) in each. The following are petrographic observations/descriptions of phase relationships and textures, accompanied by photomicrographs (figures) of some of the more common features and textures associated with each. Since these microscopy mounts were produced using crushed grains of the original samples, the textures (angular) and average sizes of these grains (0.5 – 4.0 mm) are consistent for both samples and meet the size specification for HFST applications. What differs within and between these samples are the types of mineral phases present, their respective textures and relationships to each other, and the environments in which they formed.

4.4.3.1 HFST Taconite

Two predominant opaque mineral phases totaling approximately 20.6% by weight were identified in the HFST Taconite sample. Hematite Fe_2O_3 (18.9%) and magnetite Fe_3O_4 (1.7%) were observed both separately and as magnetite-hematite transformation within the sample. A third opaque phase was also detected in the XRD analysis, however, pyrite FeS_2 (0.7%) was not observed in petrographic observation.

Hematite textures occur commonly as subhedral to euhedral individual blade-like crystals, and as small, but massive conglomerates of grains (Figure 4.16; Photomicrograph 1). The individual hematite crystals range in size 10 – 20 µm and can be clustered together, resembling massive hematite up to 500 µm (Figure 4.17; Photomicrograph 2). A third occurrence observed as fine-grained agglomerations or weakly bedded, which may be related to recrystallization or the mode of deposition in higher energy environments. These agglomerates are typically sub-rounded aggregates ranging 0.1 to 2.0 mm (2000 µm) in size (Figure 4.18; Photomicrograph 3).

Figure 4.16. Photomicrograph 1. (10X) typical hematite blades and masses within quartz matrix

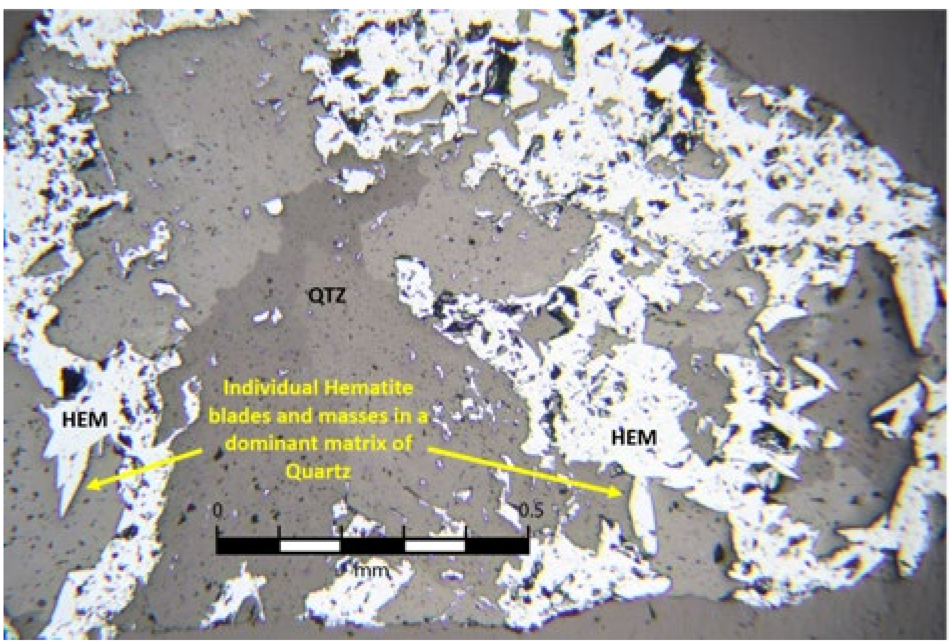


Figure 4.17. Photomicrograph 2. (50X) detailed hematite blades

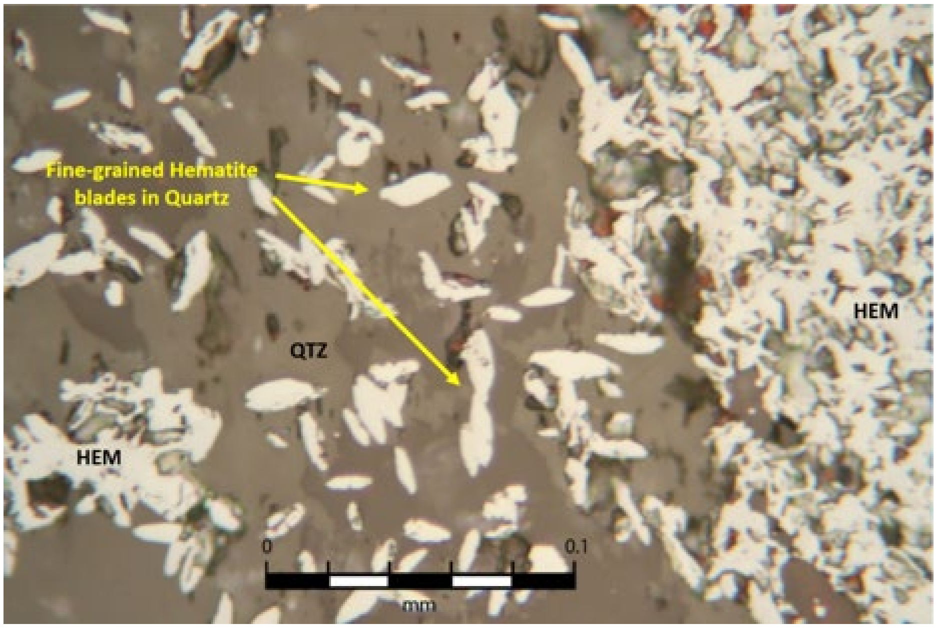
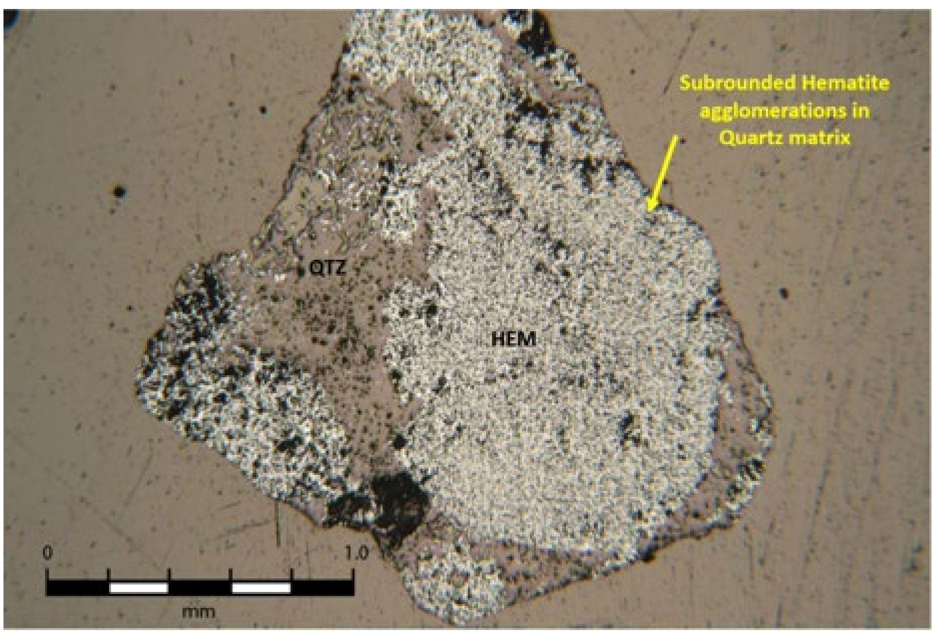


Figure 4.18. Photomicrograph 3. (5X) subrounded agglomerations of hematite



The substantial weight percent of hematite compared with that of magnetite indicates that the oxidative transformation of magnetite to hematite is mostly complete in this sample and is often observed in the approximate proportions as indicated by the XRD analysis. Magnetite was typically observed as euhedral (octahedral) to subhedral individual crystals coexisting with crystals and masses of hematite (Figure 4.19; Photomicrograph 4). Magnetite grain sizes ranged 50 – 250 µm, and in various stages of oxidation to hematite. In some locations, where hematite being the dominant iron-oxide phase, the magnetite was visibly transformed to hematite (Figure 4.20; Photomicrograph 5). In other observations, the original octahedral magnetite was just starting the oxidation transformation into hematite (Figure 4.21; Photomicrograph 6). The higher percentage of hematite versus magnetite is characteristic of taconite tailings from which the HFST aggregate is produced.

Figure 4.19. Photomicrograph 4. (10X) coexisting hematite and magnetite phases in a grain

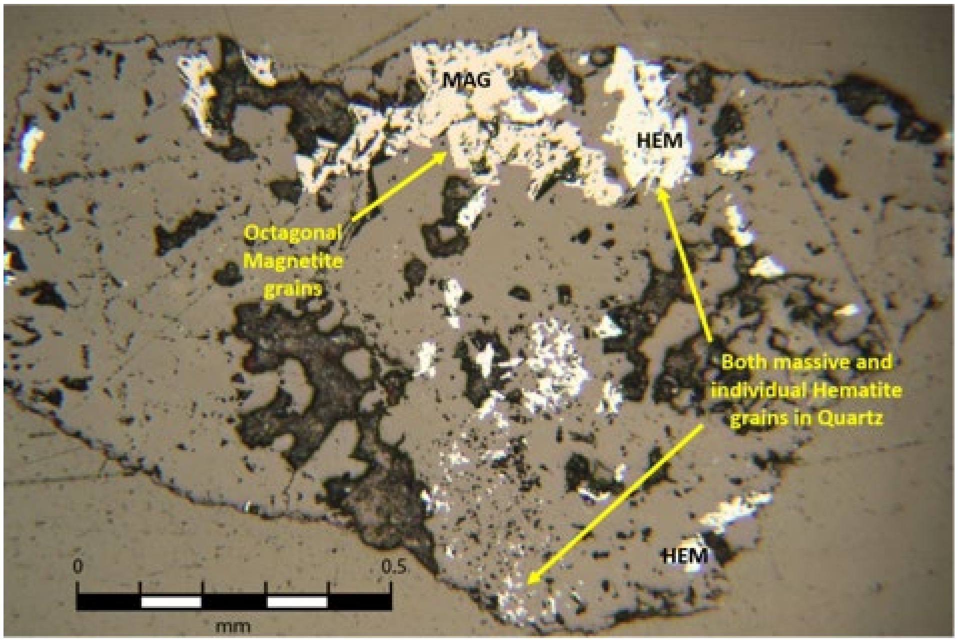


Figure 4.20. Photomicrograph 5. (20X) transformational magnetite to hematite

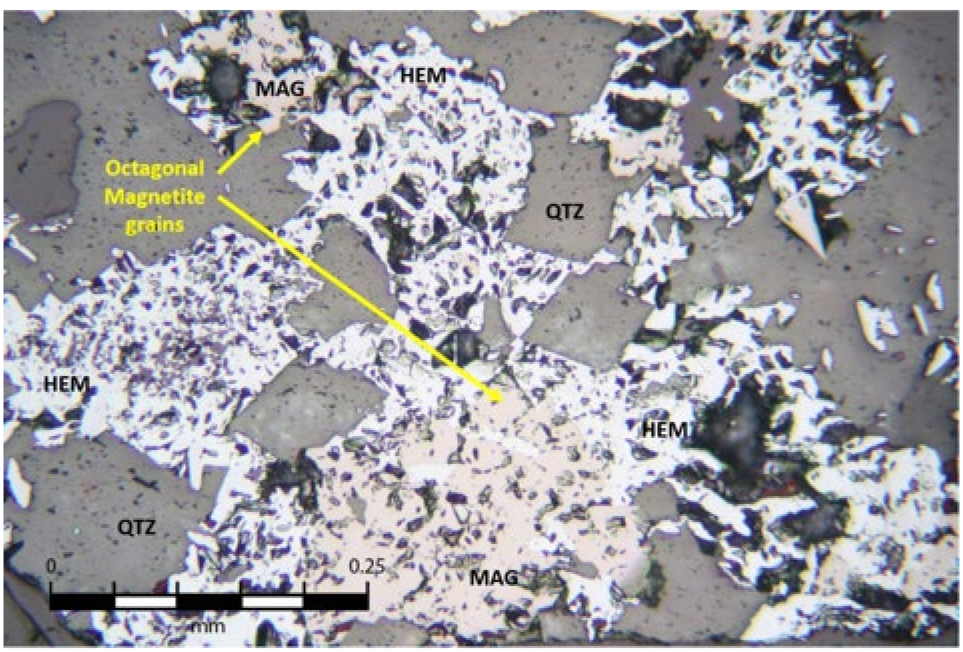
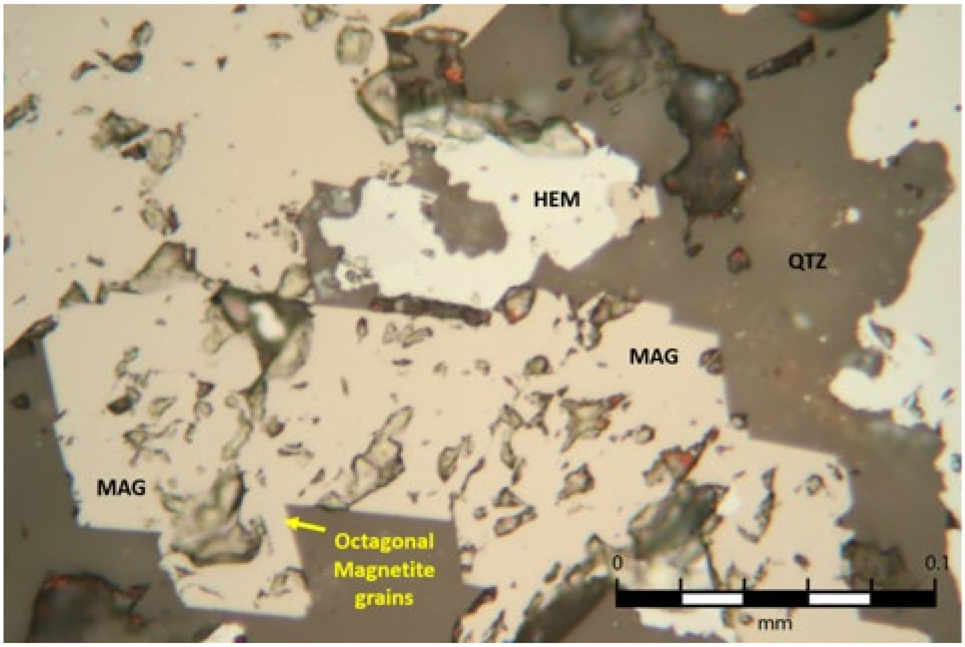


Figure 4.21. Photomicrograph 6. (50X) magnified detail of octahedral magnetite crystals



4.4.3.2 HFST Calcined Bauxite

The calcined bauxite, formed through refractory processes (from 1000 ˚C to 1500 ˚C or greater) created a uniform textured porcelain-like sample, containing a predominant oxide/silicate corundum Al_2O_3 (84.9%), mullite $3Al_2O_32SiO_2$ (11.9%) and quartz SiO_2 (0.9%) matrix. Because of the similarities between these main mineral phases, it was difficult to distinguish between them using reflected-light microscopy. In addition to the mineral phases, approximately 10% irregular-shaped voids/cavities, averaging 50 µm, were distributed uniformly across the sample (Figure 4.22; Photomicrograph 7); these voids are likely reflective of the high-temperature (calcination) process used to manufacture calcined bauxite. Because the matrix is dominated by one non-opaque mineral phase, most of the crystals/grains that are observed are likely corundum, which occurs as subhedral/sub-rounded randomly oriented prisms with a uniform size of 10 – 50 µm and/or aspect ratio of 5:1.

Two opaque mineral phases totaling approximately 2.2% by weight were identified in the HFST Calcined Bauxite sample. The rutile TiO_2 (1.5%) and hematite Fe_2O_3 (0.7%) were observed as minor, interstitial phases to a predominant matrix. These two oxide phases, however, were difficult to distinguish from each other at the maximum magnification. Nonetheless, the opaque minerals occurred as subrounded droplets/grains between the matrix prisms (corundum) and ranged in size 5 – 20 µm (Figure 4.23; Photomicrograph 8).

Figure 4.22. Photomicrograph 7. (20X) typical matrix texture (including voids) of calcined bauxite

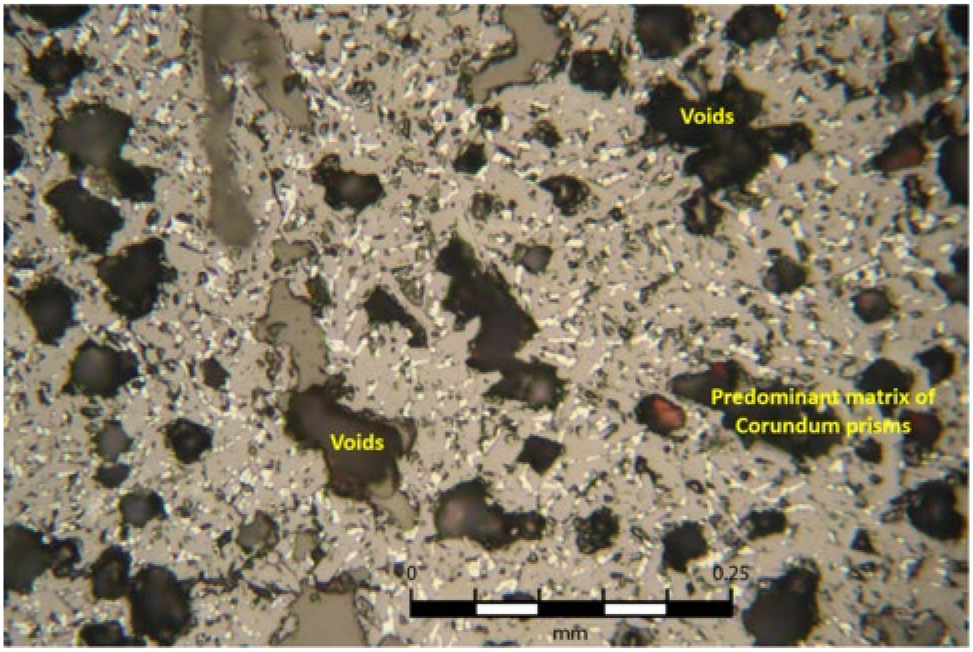
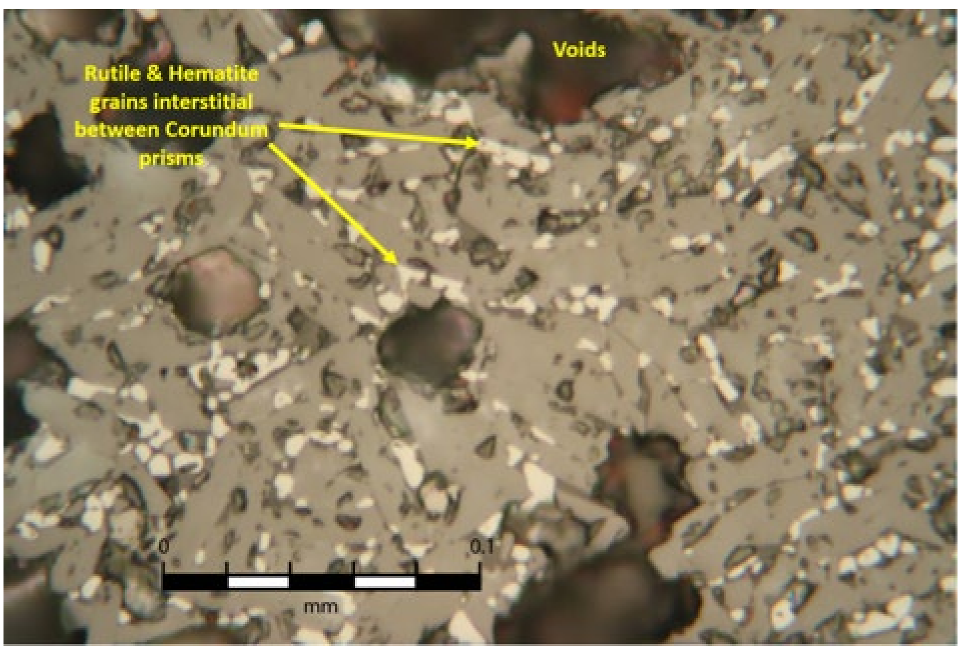


Figure 4.23. Photomicrograph 8. (50X) interstitial rutile and hematite between a predominant corundum prismatic matrix



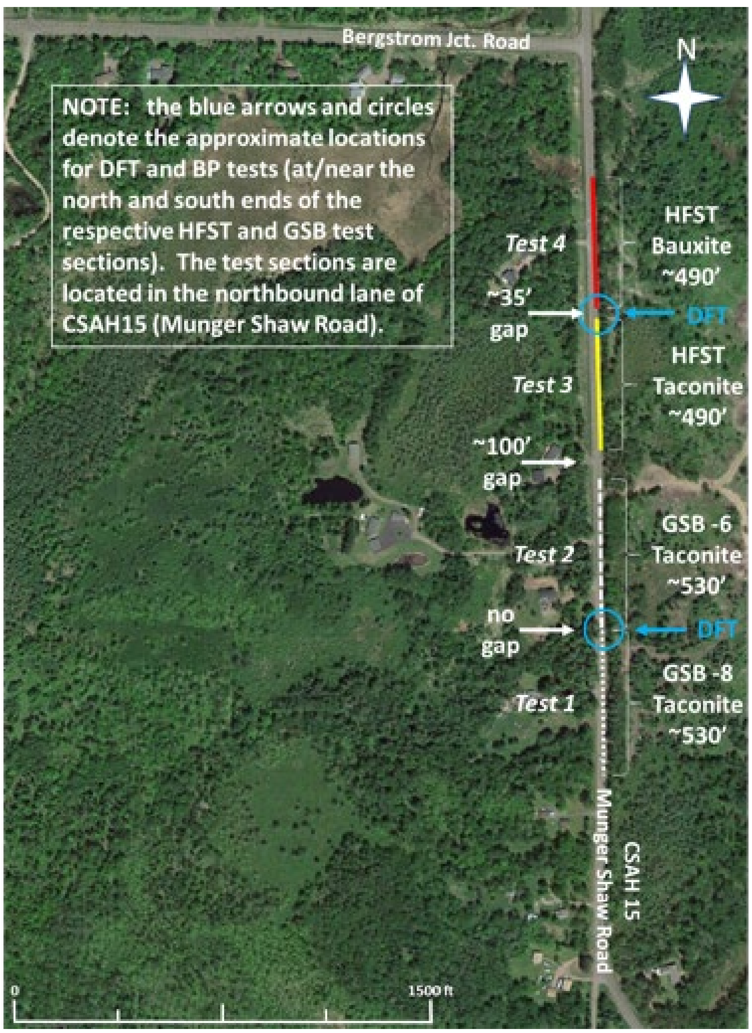
The data presented in chapter 4 provides a baseline for evaluating aggregate wear and condition at the project's test section location as discussed in the next chapters.

Chapter 5: Test Section Preparation and Installation

5.1 Introduction

This chapter presents the pavement test section installation phase of the project. Installation of pavement surface treatment test sections, including sections comprised of high friction surface treatment (HFST) using calcined bauxite and Mesabi friction aggregate (taconite), took place at the CSAH-15 location in St. Louis County (Figure 5.1). The test segments were installed over pavement that had previously received a traditional chip seal.

Figure 5.1. Project location map showing pavement surface treatment test sections



In preparation for these activities, the PI was in communication with the project's Project Coordinators (PC) David Glyer and Brent Rusco; Technical Liaison (TL) Tracey Von Bargen (Grant County); and St. Louis

County Traffic Engineer and project Technical Advisory Panel (TAP) member, Victor Lund; the project's co-Investigators, Professors Mihai Marasteanu (UMTC) and Manik Barman (UMD); the HFST resin/epoxy provider (Sika Corporation); the contractor ultimately chosen to install the pavement treatment test sections (Fahrner Asphalt Sealers LLC); and the taconite friction aggregate provider (Optimal Aggregates LLC). The PI also coordinated with the NRRI's Environmental Health & Safety Manager, Jean Cranston, to conduct respirable dust monitoring during the HFST test section installations. The results of her sample work are presented in chapter 6.

5.2 Test sections

When the project was first conceived, a 50:50 blend of taconite and bauxite was considered. However, discussions with a contractor and an aggregate producer suggested that the cost of bauxite and the difficulty of doing specialized blending (in advance or on-site at a project location) of the two specialty aggregates made 50:50 blending a challenge for contractors and local road authorities to adopt as a practical cost-effective option, at least at this time. Furthermore, the micro surfacing mix design being considered for two of the test sections was proving difficult to formulate due to insufficient fines (-100 and -200 mesh) in the source taconite aggregate. Therefore, an alternative to micro surfacing, a GSB-based system licensed to and employed by Fahrner Asphalt Sealers LLC (Fahrner) called "Friction Seal" was discussed during a Zoom meeting on April 8 by project PI Larry Zanko, project TL Tracey Von Bargen, and project test location host and TAP member, St. Louis County Traffic Engineer Victor Lund. It was agreed that the Friction Seal system was a potentially attractive pavement treatment option to consider given the thrust of the project: greater utilization of taconite aggregate materials for local road projects as a lower cost alternative to calcined bauxite.

A follow-up meeting took place at the NRRI on May 19, 2021. Following brief introductions, project TL Tracey Von Bargen presented background about pavement surface treatments and explained why the project was important to the LRRB and county highway departments. The project PI presented additional information about the project location and a description of the anticipated four test sections. The May 19 meeting also provided an opportunity to learn more about the GSB-based system and discuss it in greater detail with Brian Cox of Fahrner and with the taconite friction aggregate provider, John Vander Horn of Optimal Aggregates LLC. The GSB-based system has both pavement preservation and enhanced friction characteristics, but it was stressed that it should not be confused with a typical resin/epoxy based HFST system, such as that planned for project Test Sections 3 and 4 and used by St. Louis County at several horizontal curve locations in 2020. The friction numbers for a typical HFST system should be much higher than those of the GSB-based Friction Seal system.

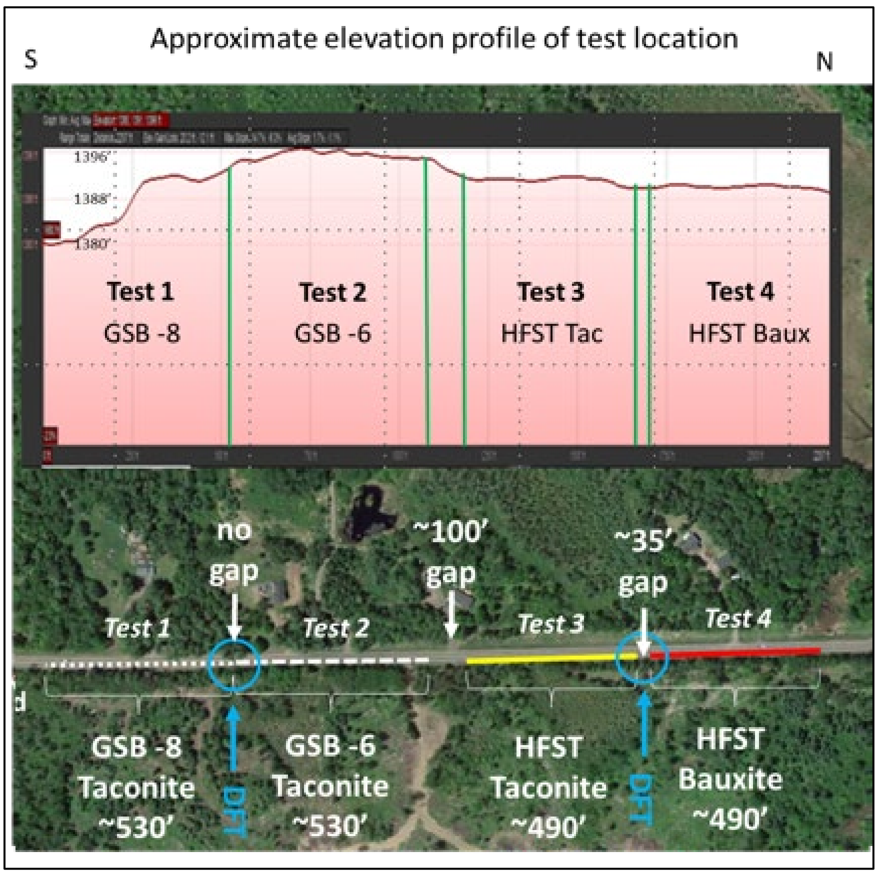
The Friction Seal system uses a specialized truck to simultaneously deploy aggregate and a GSB-based emulsion to the road surface at a specific application rate. Its usual aggregate gradation is 100% passing a #8 (2.36mm) screen. Brian Cox was asked if the system could accept a coarser top size (#6, or 3.35mm), similar to the top size used in an epoxy/resin based HFST system. Because the emulsion and aggregate deployment rate is fine-tuned for the current Friction Seal specification, confirmation was needed about how this gradation change could be used (for example, would a slight increase in the quantity of emulsion used per square yard of pavement be required?). Confirmation was subsequently received from Fahrner.

Therefore, the four test sections in addition to a control (the existing chip sealed pavement) were agreed upon to consist of the following, as shown from south to north in Figure 5.1:

- **Test Section 1:** Taconite applied using a standard gradation GSB-based system
- **Test Section 2:** Taconite applied using a GSB-based system at a slightly coarser gradation than Test 1
- **Test Section 3:** Taconite applied with epoxy/resin – Typical HFST installation
- **Test Section 4:** Bauxite applied with epoxy/resin – Typical HFST installation

The test location's approximate elevation profile is shown in Figure 5.2.

Figure 5.2. Approximate elevation profile of pavement surface treatment test sections



Based on the May 19 meeting, the project PI requested a quote from Fahrner that included the installation of two GSB-based test sections (1 and 2) in addition to the two epoxy/resin-based HFST test sections (3 and 4). Also requested was a more detailed breakdown of cost components (mob, demob, prep, etc.) and per square yard cost differential between an epoxy-based HFST vs a Friction Seal application for a more typically sized (multi-lane-mile) project. As was pointed out at the meeting, much of the total cost per square yard for our research sections is skewed by mob and demob costs (mob and demob cost being the same regardless of project size). The typical per square yard cost for the GSB-based system is considerably less than a standard epoxy/resin-based HFST system, as provided by Farhner.

- GSB Friction Seal is ~ $4.00 / SY when doing projects greater than 15,000 SY
- High Friction Treatment is ~ $25.00 / SY when doing projects greater than 15,000 SY

Following receipt of the quote on June 9, the project PI presented the options to the project TL and the project TAP member advisor for consideration. Considered was Fahrner's local/regional presence and its capacity for mobilizing crews and equipment specific to both types of pavement treatments (epoxy-based and GSB/asphalt-based) and completing all four test section installations in a single day, thereby minimizing traffic disruption and the need for another (separate) day of traffic control. Fahrner also informed the team that it was unnecessary to micro-mill the existing pavement prior to installing the epoxy-based HFST sections. For context, St. Louis County had performed micro milling in advance of a 2020 HFST installation that was done on top of a new pavement section. In that situation, the micro milling was done to maintain an even transition from one pavement surface profile to the next. The situation was different for the current test project and simplified test section preparation considerably, avoiding an extra step and additional cost that St. Louis County would otherwise have been responsible for.

The two GSB-based treatment options also fit well with the project's overall objective of evaluating the cost and performance of one or more systems that could: 1) expand the use of taconite aggregate; and 2) have much broader appeal to low volume road end-users, both key considerations for LRRB/MnDOT. Lastly, supply chain issues were impacting epoxy resin availability throughout the country in late spring and early summer of 2021, which threatened to delay the delivery of the donated epoxy resin needed for the HFST test section installations and consequently put the project significantly behind schedule. Fortunately, Fahrner had enough of the same two-part resin (see Appendix C) in its Wisconsin inventory and made arrangements with the resin donator (Sika Corporation) to replace – later – the resin Fahrner provided for this project. Taking all these factors into consideration – not the least of which was project timing – the consensus of the project PI, TL, and TAP representative was to proceed with the test section installations, using Fahrner as the contractor. Contracting was finalized in late July, and the four test sections were installed on July 29, 2021.

5.2.1 Preparation

On July 8, the project PI applied for a St. Louis County Right-of-Way Permit for the HFST test section location. The $200 application fee was waived, and the permit granted by St. Louis County. Fahrner established traffic control at the north and south ends of the project location the morning of July 29, 2021. Fahrner secured a staging area for personnel, equipment, and materials (Figure 5.3) approximately 1 mile from the project location. The project PI met Brian Cox of Fahrner and John Vander Horn of Optimal Aggregates at the staging area at 7AM before driving to the project location to mark the approximate starting and ending points of each test section. Fahrner personnel followed by cleaning the existing pavement with compressed air.

Figure 5.3. Staging area, showing super sacks of aggregate and totes containing two-part epoxy resin (left), and loading of aggregate for GSB-based pavement treatment (right).

5.2.2 Installation and documentation

5.2.2.1 Friction Seal Test Sections

The two GSB Friction Seal system test sections (cells) were installed in the morning of July 29. As described previously, the GSB Friction Seal system combines pavement preservation with friction enhancement, using a specialized chip spreader/distribution truck (Figure 5.4) that places the GSB liquid followed immediately by aggregate distribution. The system uses a narrower HFST-type aggregate gradation than micro surfacing does. The aggregate used in this system was taconite, donated by Optimal Aggregates LLC. Each sack contained approximately 3000 lbs. of aggregate.

Figure 5.4. GSB Friction Seal chip spreader/distribution truck

Brian Cox of Fahrner provided the following details about the two GSB Friction Seal sections:

Test Cell Number 1: (~ 530-foot section; 645 SY)

- 0.20 gals / SY GSB-88 Concentrate with 5% latex
- 2.5 lbs / SY of Minus #8 taconite sand

Test Cell Number 2: (~ 530-foot section; 645 SY)

- 0.22 gals / SY GSB-88 Concentrate with 5% latex
- 3.0 lbs / SY of Minus #6 taconite sand

Each test section took less than 5 minutes to install. Note the slightly heavier application of aggregate and liquid for Test Cell 2, compared to the standard Friction Seal application rate. A series of photos in Figure 5.5 shows the spreader/distribution truck and the deployment of the Friction Seal treatment. Additional photos and video were taken by the NRRI's Marketing Specialist, Jeremy Weizel, to document the GSB and HFST installations.

Figure 5.5. Installation of minus #8 Friction Seal: (a) start of installation; (b) close-up of spreader and deployment of GSB and aggregate; (c) freshly-installed; and (d) post-installation

Figure 5.6 shows a completed test section and a close-up image taken before the GSB-based emulsion broke (set) (inset Figure 5.6). Under sunny, warm, and dry conditions, the installation can typically accept traffic within an hour. The installation condition on the morning of July 29 was cool and shaded, which contributed to a longer set time.

Figure 5.6. Completed Friction Seal test section and close-up image (inset)

5.2.2.2 HFST Test Sections

The two HFST system test sections (cells) were installed in the afternoon of July 29, one using calcined bauxite friction aggregate and the other using taconite friction aggregate. The taconite HFST aggregate was again donated by Optimal Aggregates LLC. Duct tape was applied to the fog and center lines ahead of time to prevent the lines from being covered during the test section installations (Figure 5.7).

Figure 5.7. Taping of fog line prior to HFST installation (left); fully-taped lines (right)

The recommended HFST resin application rate achieves coverage of 25 to 32 ft^2 per gallon and a thickness of 60 mils, and aggregate is applied at 12-15 lb/yd^2. A 1:1 two-part resin product (Sikadur®-22 Lo-Mod, Appendix C) provided by Sika Corporation was used, topped with the project's taconite and calcined bauxite HFST aggregates.

The HFST system can be installed using an automated or a non-automated high-friction rig (Figure 5.8a and Figure 5.8c, respectively). The automated rig was unavailable, so the non-automated method was used for the test section installations. As Figure 5.8b shows, the automated rig mixes and delivers the two-part epoxy resin from two separate tanks (marked "A" and "B") to the pavement while in moving mode, whereupon the resin is evenly spread with a lane-width "squeegee" at the rig's rear to which high friction aggregate is distributed and placed immediately. In contrast, the non-automated rig delivers the "A" and "B" resin components via the blue (component A) and red (component B) supply lines shown in Figure 5.8d to a mixing wand. Both resin components are combined at the nozzle end and are applied to the pavement. A worker follows with a hand-held squeegee to evenly spread the resin across the width of the lane. A final worker follows and applies the friction aggregate. The aggregate is delivered pneumatically from a hopper and broadcast to completely cover the resin at the specified application rate per square yard.

The non-automated method is more labor-intensive and thus slower. Each test section took approximately two hours to install (about twice the time of automated rig deployment), and its pneumatic aggregate delivery system likely generated more dust (Figure 5.8) than the automated rig would have, given their different mechanisms of resin and aggregate deployment. The NRRI's Environmental Health & Safety Manager, Jean Cranston, conducted respirable dust monitoring during the HFST test section installations; the results of her sampling work are presented in Chapter 6.

Figure 5.8. HFST equipment options: (a) automated HFST rig; (b) close up of resin and aggregate delivery end of automated HFST rig; (c) non-automated HFST rig showing loading of aggregate to hopper at project staging location; and (d) non-automated method for delivery and application of resin and aggregate from the non-automated HFST rig, showing installation of taconite HFST aggregate to Test Section 3. Images a and b courtesy of Fahrner Asphalt Sealers

Brian Cox of Fahrner provided the following details about the two installed HFST sections:

Test Cell Number 3: (~ 490-foot section; 530 SY)

- 0.36 gals / SY Sikadur-22 Lo-Mod FS two-part epoxy
- 14 lbs / SY of taconite sand retained

Test Cell Number 4: (~ 490-foot section; 530 SY)

- 0.36 gals / SY Sikadur-22 Lo-Mod FS two-part epoxy
- 14 lbs / SY of calcined bauxite retained

Figure 5.9 shows the post-installation appearance of both HFST test sections.

Following installation of the HFST sections, contractor personnel cleared excess HFST aggregate from the pavement using compressed air and brooms. All work related to the test section installations was completed by late afternoon of July 29, 2021.

Figure 5.9. HFST test sections, post-installation: taconite test section, looking south (top left); close up of taconite HFST (top right); calcined bauxite test section, looking south (bottom left); close up of calcined bauxite HFST (bottom right); relative size of both aggregate types (inset image)

5.2.3 Post-installation follow-up

Test segment condition monitoring, skid resistance testing, field performance tracking, lab testing review, documentation, and conference presentations comprised the next (post-installation, Year 1) phase of the project. Information and data collection began in August of 2021 to establish the post-test section (and control) baselines, using the Dynamic Friction Tester (DFT) and British Pendulum (BP) (August 5), and MnDOT's Road Doctor (August 11) and Locked-Wheel Skid Tester (August 17). These tests continued approximately every six months for the duration of the project, ideally in the fall, before snow plowing started, and in springtime following winter snow plowing.

Chapter 6: Collection, Quantification, and Characterization of Fugitive Dust Particulate Matter (PM)

6.1 Introduction

Task 6 represented the dust (particulate matter, or PM) monitoring and assessment phase of the project, to gauge the relative “dustiness” (PM concentration per unit volume of air) of the taconite and calcined bauxite aggregates, and the composition of the potentially respirable PM fraction generated as both were being installed, gravimetrically, mineralogically, chemically, and microscopically.

Two approaches were planned. The first approach was to conduct on-site monitoring/sampling, which would have a better chance of capturing the dust generated during the field installations. The second approach would be to use the NRRI’s Micro Orifice Uniform Deposit Impactors (MOUDIs) in a more controlled test, to characterize the size distribution and composition of dust generated by both aggregate types. It was determined that a controlled test – rather than trying to use the MOUDIs outdoors at the job site where the MOUDIs would be stationary relative to the moving pavement treatment installations, and perhaps only briefly exposed to dust and the vagaries of wind direction – would be a better option. However, personnel availability and scheduling conflicts prevented the controlled MOUDI test work from being performed in 2021.

The PI coordinated with the NRRI’s Environmental Health & Safety Manager, Jean Cranston, to conduct respirable dust monitoring during the HFST test section installations only; installations of the two GSB test sections would happen too quickly (~ 5 minutes, each) to allow enough time to obtain meaningful data. The on-site HFST installation monitoring focused on measuring inhalable dust. A full report by Ms. Cranston was submitted to the PI (Figure 6.1) and its findings are presented and summarized on the following pages.

Figure 6.1. Report submitted by the NRRI’s Jean Cranston to the project PI

Natural Resources
Research Institute
University of Minnesota Duluth
Driven to Discover

Duluth Laboratories & Administration
5013 Miller Trunk Highway
Duluth, Minnesota 55811

Date: **August 6, 2021**

TO: Lawrence Zanko,
NRRI Senior Research Program Manager

FROM: Jean Cranston, CIH, CSP
NRRI Safety Manager

RE: Dust sampling during aggregate applications

6.2 HFST test section installation dust monitoring report

On July 29, 2021, NRRI Safety completed real-time aerosol monitoring to evaluate dust with an aerodynamic diameter of 10 micrometers (µm) or smaller (PM10) during application of dry aggregates. The monitoring occurred during the application of a tailings-based aggregate and a bauxite-based aggregate on the Munger Shaw Road in Duluth, MN. The purpose of the air monitoring was to compare dust levels during the application of the two high friction aggregates.

6.2.1 Methods

Epoxy and aggregate were loaded separately into a Fahrner Asphalt high friction rig (Figure 6.2a). The aggregate was manually sprayed on top of the epoxy (Figure 6.2b). Air concentrations for Sample 1 were collected during the application of the tailings-based aggregate and air concentrations for Sample 2 were collected during application of the bauxite-based aggregate (refer to results).

Figure 6.2. High friction rig (a); closeup of application hose (b) application process

As calibrated (calibration date of March 2, 2021), a TSI, Inc. DustTrak (Model 8520) was used to evaluate the concentrations of inhalable dust during two separate applications (Figure 6.3). The Dust Trak measures particles using a laser photometer and light scattering technology. The data collection began approximately 15 minutes after each start-up to allow time for the equipment to warm up. An average aerosol concentration was recorded every minute for a total of 30 minutes.

Figure 6.3. DustTrak Model 8520 (image source: TSI)

A 10-µm inlet was used with the DustTrak so that results could be compared to hazardous occupational dust. Dust that is 10 µm or smaller in size is considered more of an occupational hazard than larger size particles as they have a greater potential to penetrate the thoracic and respirable areas of the respiratory tract.

An industrial hygienist walked along the shoulder of the road and moved with the mobile operation while holding DustTrak (Figure 6.4). The samples were collected 30-50 feet downwind of the application process (Figure 6.5). On the day of the sampling there was an air quality alert due to nearby forest fires. According to DustTrak, the average baseline aerosol concentration on the day of monitoring was 0.213 mg/m^3. The temperature was 72 degrees Fahrenheit (22 degrees Celsius) with 11 mph (18 km/h) winds.

As described in Project Task Report 5, The HFST system can be installed using an automated or a non-automated high-friction rig. The automated rig was unavailable, so the non-automated method was used for the test section installations. The non-automated rig delivers two resin components via supply lines to a mixing wand. Both resin components are combined at the nozzle end and are applied to the pavement. A worker follows with a hand-held squeegee to evenly spread the resin across the width of the lane. A final worker follows and applies the friction aggregate (Figure 6.4). The aggregate is delivered pneumatically from a hopper and broadcast to completely cover the resin at the specified application rate per square yard. The non-automated rig's pneumatic aggregate delivery system likely generated more dust than the automated rig would have.

Figure 6.4. Dust monitoring by industrial hygienist upwind of HFST aggregate deployment.

Figure 6.5. Dust monitoring by industrial hygienist downwind of HFST aggregate deployment

6.2.2 Results and discussion

Average air concentrations over 30 minutes for both aggregates were below both the OSHA Permissible Exposure Limit (PEL) and the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV) for inhalable dust (Table 6.1). The average for the bauxite sample was slightly lower than the average for the tailings sample. The averages indicate that under these conditions, if an employee stood 30-50 feet down wind of application for an 8-hour work shift, they would be below occupational exposure limits for inhalable dust.

The concentrations of respirable dust and silica were not evaluated. Personal sampling for respirable dust and silica should be completed to determine personal exposure limits and compare them to respirable occupational exposure limits. Please note that according to safety data sheets (Appendix E) the tailings sample contains >50% silica while the bauxite sample contains <10%.

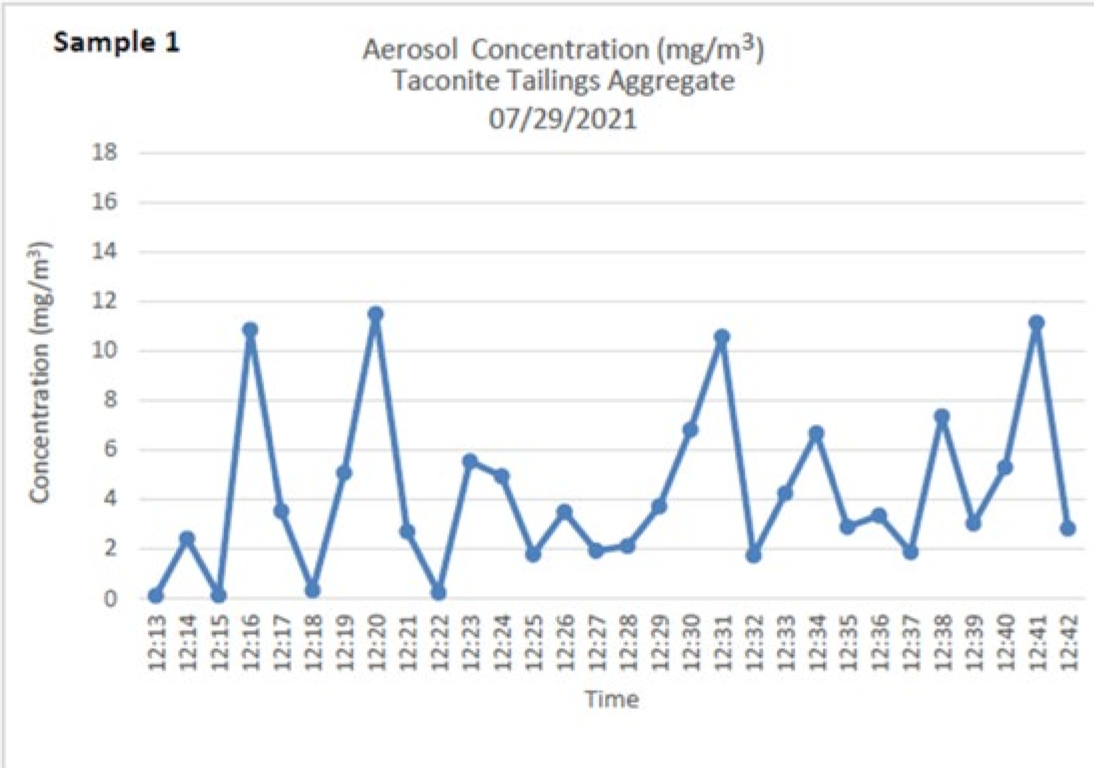
Table 6.1. Summary table: concentrations of inhalable dust for HFST aggregate relative to OSHA and ACGIH exposure limits (Units = mg/m^3)

Sample #	Aggregate Type	Max.	Min.	Avg.	OSHA PEL (Inhalable)	ACGIH TLV (Inhalable)
1	Taconite Tailings	11.50	0.11	**4.27**	15	10
2	Bauxite	15.60	0.09	**3.88**	15	10

Note: The taconite tailings aggregate contains >50% silica and respirable dust and silica concentrations were not evaluated.

Figure 6.6 shows the aerosol concentrations (mg/m^3) for both aggregate types during their installations, and Tables 6.2 to Table 6.4 shows the data files upon which the Figure 6.6 plots are based.

Figure 6.6. Plots of aerosol concentrations during HFST installation monitoring for Taconite HFST aggregate (Sample 1) and Bauxite HFST aggregate (Sample 2).



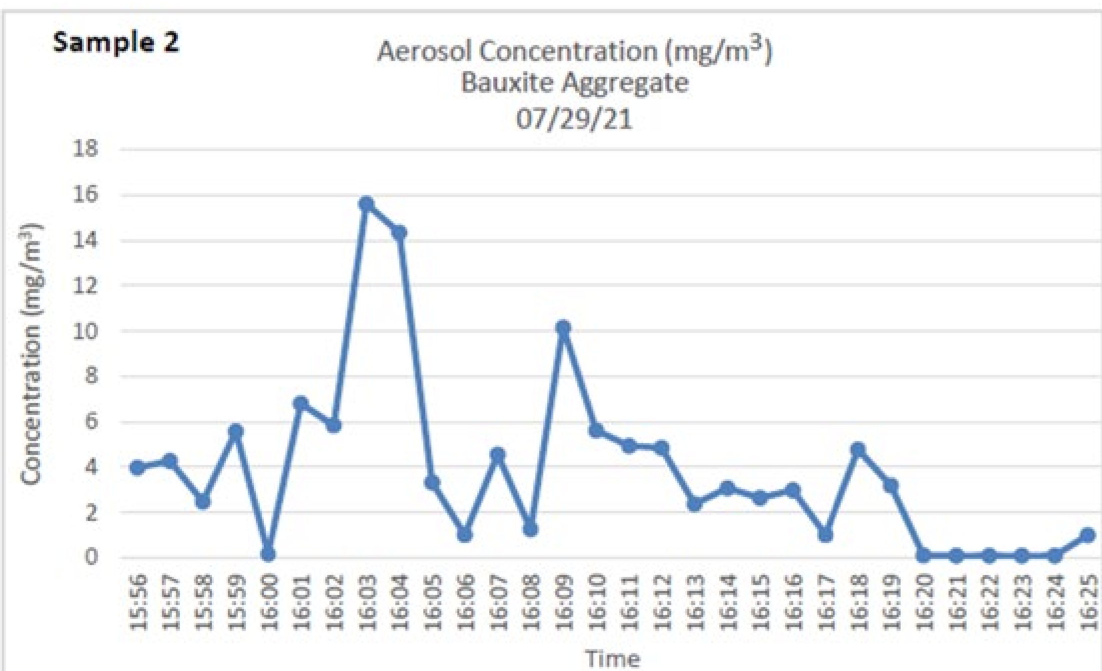


Table 6.2. Inhalable dust data collected during 30 minutes of DustTrak monitoring of taconite (Sample 1) and bauxite (Sample 2) HFST aggregate installation.

TRAKPRO REPORT	Sample 1: Taconite Aggregate		Sample 2: Bauxite Aggregate	
Column1.1	Column1.2	Column1.3	Column1.2	Column1.3
TrakPro Version 4.70 ASCII Data File				
Model:	Dust Trak		Dust Trak	
Model Number:	8520		8520	
Serial Number:	21990		21990	
Test ID:	1		2	
Test Abbreviation:				
Start Date:	07/29/2021		07/29/2021	
Start Time:	12:12:33		15:55:26	
Duration (dd:hh:mm:ss):	0:00:30:00		0:00:30:00	
Log Interval (mm:ss):	01:00		01:00	
Number of points:	30		30	
Notes:				

Table 6.3. Statistics of inhalable dust data collected during 30 minutes of DustTrak monitoring of taconite (Sample 1) and bauxite (Sample 2) HFST aggregate installation.

Sample 1: Taconite Aggregate		Sample 2: Bauxite Aggregate	
Column1.2	Column1.3	Column1.2	Column1.3
Channel:	Aerosol	Channel:	Aerosol
Units:	mg/m^3	Units:	mg/m^3
Average:	4.27	Average:	3.875
Minimum:	0.105	Minimum:	0.092
Time of Minimum:	12:13:33	Time of Minimum:	16:21:26
Date of Minimum:	07/29/2021	Date of Minimum:	07/29/2021
Maximum:	11.497	Maximum:	15.602
Time of Maximum:	12:20:33	Time of Maximum:	16:03:26
Date of Maximum:	07/29/2021	Date of Maximum:	07/29/2021

Table 6.4. Aerosol concentrations (mg/m³) for the inhalable dust data collected during 30 minutes of DustTrak monitoring of taconite (Sample 1) and bauxite (Sample 2) HFST aggregate installation.

TRAKPRO REPORT Sample 1: Taconite Aggregate			TRAKPRO REPORT Sample 2: Bauxite Aggregate		
Date MM/dd/yyyy	Time hh:mm:ss	Aerosol mg/m^3	Date MM/dd/yyyy	Time hh:mm:ss	Aerosol mg/m^3
07/29/2021	12:13:33	0.105	07/29/2021	15:56:26	3.970
07/29/2021	12:14:33	2.422	07/29/2021	15:57:26	4.276
07/29/2021	12:15:33	0.120	07/29/2021	15:58:26	2.484
07/29/2021	12:16:33	10.860	07/29/2021	15:59:26	5.574
07/29/2021	12:17:33	3.523	07/29/2021	16:00:26	0.174
07/29/2021	12:18:33	0.323	07/29/2021	16:01:26	6.807
07/29/2021	12:19:33	5.073	07/29/2021	16:02:26	5.834
07/29/2021	12:20:33	11.497	07/29/2021	16:03:26	15.602
07/29/2021	12:21:33	2.696	07/29/2021	16:04:26	14.335
07/29/2021	12:22:33	0.226	07/29/2021	16:05:26	3.324
07/29/2021	12:23:33	5.536	07/29/2021	16:06:26	1.018
07/29/2021	12:24:33	4.940	07/29/2021	16:07:26	4.555
07/29/2021	12:25:33	1.777	07/29/2021	16:08:26	1.257
07/29/2021	12:26:33	3.498	07/29/2021	16:09:26	10.144
07/29/2021	12:27:33	1.926	07/29/2021	16:10:26	5.609
07/29/2021	12:28:33	2.118	07/29/2021	16:11:26	4.928
07/29/2021	12:29:33	3.718	07/29/2021	16:12:26	4.843
07/29/2021	12:30:33	6.811	07/29/2021	16:13:26	2.371
07/29/2021	12:31:33	10.574	07/29/2021	16:14:26	3.066
07/29/2021	12:32:33	1.732	07/29/2021	16:15:26	2.635
07/29/2021	12:33:33	4.251	07/29/2021	16:16:26	2.984
07/29/2021	12:34:33	6.672	07/29/2021	16:17:26	1.015
07/29/2021	12:35:33	2.893	07/29/2021	16:18:26	4.777
07/29/2021	12:36:33	3.346	07/29/2021	16:19:26	3.190
07/29/2021	12:37:33	1.874	07/29/2021	16:20:26	0.115
07/29/2021	12:38:33	7.359	07/29/2021	16:21:26	0.092
07/29/2021	12:39:33	3.033	07/29/2021	16:22:26	0.093
07/29/2021	12:40:33	5.287	07/29/2021	16:23:26	0.092
07/29/2021	12:41:33	11.137	07/29/2021	16:24:26	0.093
07/29/2021	12:42:33	2.817	07/29/2021	16:25:26	0.991

Whereas the aerodynamic diameter of inhalable dust monitored during the HFST aggregate deployments is 10 µm or smaller (i.e., PM10), *respirable* dust is typically referred to as PM2.5, meaning that its aerodynamic diameter is 2.5 µm or smaller. In other words, PM2.5 is a subset of PM10. The NRRI's Micro Orifice Uniform Deposit Impactors (MOUDIs) could provide this information in a more controlled test in the future, to characterize the size distribution and composition of dust generated by both aggregate types.

As described by Monson Geerts et al. (2019), *"The MOUDI is designed for precision, high-accuracy sampling. It operates at a flow rate of 30 L/min. and has 10 stages with aerodynamic diameter cut sizes ranging from 18 µm to 0.056 µm (Figure 6.7 and Figure 6.8). This size-fractionating of the aerosol particles allows for the designation of the PM into specific size classifications including PM1, PM2.5, and PM10, which is part of the characterization as well as important for assessing mass weight. Based on the aerodynamic diameter of particles and the MOUDI stage in which these particles are impacted, the size fractions can be related to general areas of the respiratory system that would be affected during breathing by particles of this size."*

Figure 6.7. Micro-Orifice Uniform Deposit Impactor (MOUDI) (from: Monson Geerts et al., 2019)

Figure 6.8. MOUDI cascade impactor stages and ranges (from: Monson Geerts et al., 2019)

Stage #	[illegible]	[illegible]	[illegible]	Range µm	Log Mean [1]Diameter µm	[2]General Areas of Human Respiratory System Affected
0				30.000 - 18.000	23.491	Nasopharyngeal Region
1				18.000 - 10.000	13.610	
2				10.000 - 5.620	7.601	
3				5.620 - 3.160	4.273	Trachea, Bronchial and Bronchiolar Region
4				3.160 - 1.780	2.404	
5				1.780 - 1.000	1.353	
6				1.000 - 0.562	0.760	Alveolar Region
7				0.562 - 0.316	0.427	
8				0.316 - 0.178	0.240	
9				0.178 - 0.100	0.135	
10				0.100 - 0.056	0.076	
F				0.056 - 0.000	0.000	

[1]Aerodynamic Diameter
[2]Marple, V., 2010, pers. com.

6.3 Summary and potential follow-up

Based on the non-automated mode of HFST aggregate deployment, this report's inhalable dust monitoring results likely reflect a higher dust-generating working environment than what might be encountered using the automated mode of deployment. Even so, the testing showed the average air concentrations over 30 minutes for both aggregates were below both the OSHA PEL and ACGIH TLV for inhalable dust.

However, the concentrations of *respirable dust* and silica were not evaluated. Personal sampling for respirable dust and silica should be completed later to determine personal exposure limits and respirable occupational exposure limits.

Chapter 7: Pavement test section monitoring and testing

7.1 Introduction

Chapter 7 presents the pavement test section monitoring and testing phase of the project. Field monitoring of installed systems and field performance tracking and testing and field specimen collection took place with MnDOT's locked-wheel skid tester (up to twice per year) and Road Doctor (Year 1 only); and testing with a Dynamic Friction Tester (DFT) and British Pendulum Skid Resistance tester by University of Minnesota Twin Cities (UMTC) and Duluth (UMD) personnel twice per year.

The activities were again coordinated by the Principal Investigator (PI) with St. Louis County Traffic Engineer and project Technical Advisory Panel (TAP) member, Victor Lund; project technical liaison (TL), Tracey Von Bargen; South Sign Supervisor for St. Louis County Public Works, Dwain Ecklund; the project's co-Investigators, Professors Mihai Marasteanu (UMTC) and Manik Barman (UMD); Mugur Turos (UMTC); and MnDOT's Christopher Nadeau, Eyoab Zegeye Teshale, Thomas Calhoon, and Gregory Larson. The PI was assisted by NRRI colleague, Sara Post, P.E.

7.2 Post-installation follow-up

Test segment condition monitoring, skid resistance testing, field performance tracking, lab testing review, documentation, and conference presentations comprised the next (post-installation, Year 1) phase of the project. The four test sections were installed on July 29, 2021, and are described in chapter 5, see Figure 5.1 and Figure 5.2.

7.2.1 Friction testing

Information and data collection began in August of 2021 to establish the post-installation test section (and control) baselines, using the DFT and BPT (August 5), MnDOT's Locked-Wheel Pavement Friction Tester (LWPFT) (August 17), and MnDOT's Road Doctor (August 11), see Figure 7.1.

The project workplan called for these tests to continue every six months (+ or -) for the duration of the project, ideally: 1) in the fall, *before* snow plowing starts; and 2) in the springtime or early summer, *after* snow plowing ends. This testing approach could show the relative impacts that rubber-tired traffic only (spring/summer/fall), and rubber-tired traffic + snow plowing (winter), have on pavement wear and friction characteristics.

The project's first post-installation, pre-snow plowing, friction tests took place on October 20, 2021, using the DFT and BP. Equipment problems prevented MnDOT's Locked-Wheel Pavement Friction Tester from being used, but a second set of Road Doctor data were collected on November 3, 2021. The project's first *post*-snow plowing friction tests took place on June 6, 2022, again using the DFT and BP.

Follow-up tests with MnDOT's Locked-Wheel Pavement Friction Tester took place in the Summer of 2022. The presentation and discussion of the DFT, BP, and LWPFT results took place afterward.

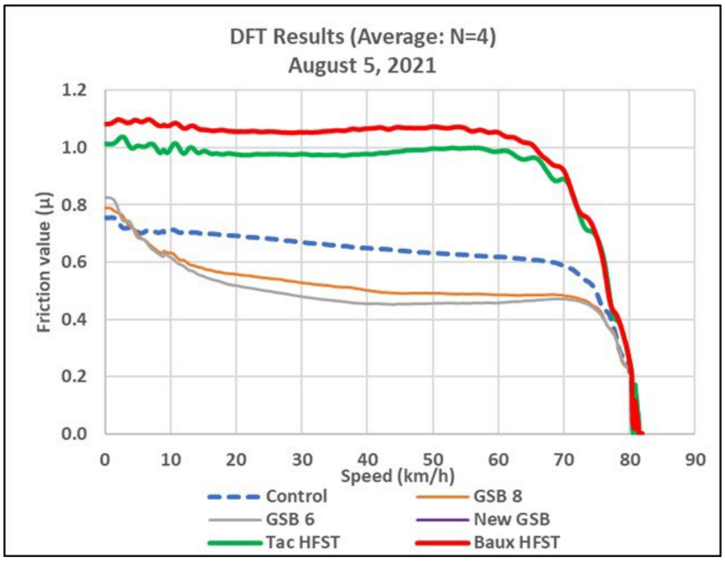
Figure 7.1. Data collection methods/equipment: A) Dynamic Friction Tester; B) British Pendulum; C) MnDOT's Locked-Wheel Pavement Friction Tester; and D) MnDOT's Road Doctor

The DFT data were collected, compiled, and summarized by Mugurel Turos, UMTC-CEGE; while the BP data were collected, compiled, and summarized by Prof. Manik Barman, UMD. They were assisted during the third tests performed on June 6, 2022 – Mugurel Turos by Enzo Mariette, a visiting student from France; and Prof. Barman by Justin Hull, an undergraduate student in civil engineering at UMD. The LWPFT data were collected and compiled by MnDOT's Christopher Nadeau.

The DFT tests were conducted within the wheel path of each test section – four replicates per test section – with the DFT device repositioned between each of the four runs to provide a more representative composite result. The DFT data (Figure 7.2 to Figure 7.4) show the taconite and bauxite HFST test sections (Tac HFST and Baux HFST) had significantly higher friction values (by over 50%) relative to the Control (existing chip sealed pavement), whereas the two GSB-based Friction Seal sections returned lower-than-expected friction values.

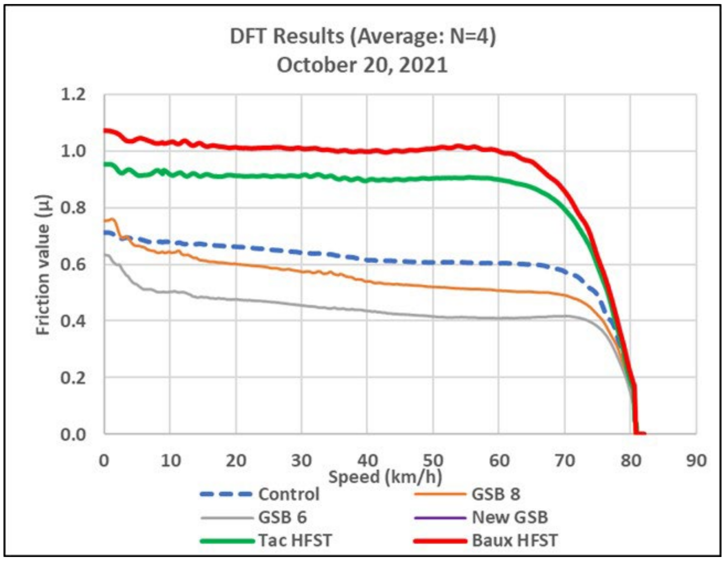
The lower friction values for the GSB-based sections led to the scheduling of a follow-up meeting on April 8, 2022, between the PI, the project TL, the project's St. Louis County TAP representative, the taconite friction aggregate provider, and the pavement treatment installation contractor. The contractor suspected that a calibration issue with the deployment equipment led to an aggregate application rate that was too low relative to the liquid emulsion application rate. As a result, the contractor coordinated with the friction aggregate provider, the PI, and St. Louis County, and a new Friction Seal test section was added during the summer of 2022. Interestingly, the friction values for the GSB 8 section measured on June 6, 2022, show an *increase*, approaching those of the Control section. According to the contractor, this increase reflects more aggregate particles being exposed as the emulsion coating is slowly abraded by traffic over time.

Figure 7.2. Dynamic Friction Tester test results: August 5, 2021 (chart and data table)



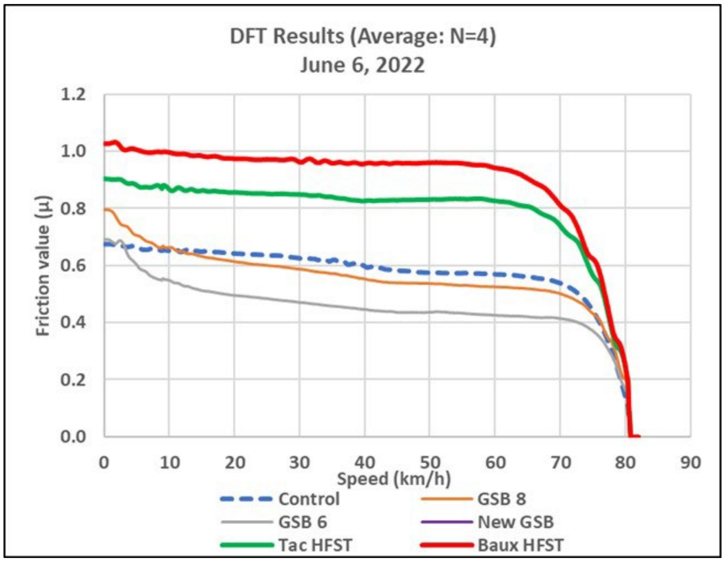
Baseline		Dynamic Friction Result Average Friction Values (4 runs per test surface)					
Speed (km/h)	Speed (mph)	Control	GSB 8	GSB 6	Tac HFST	Baux HFST	New GSB
10	6.2	0.71	0.63	0.62	1.00	1.08	NA
20	12.4	0.69	0.56	0.52	0.98	1.06	NA
30	18.6	0.67	0.53	0.48	0.98	1.05	NA
40	24.9	0.65	0.50	0.45	0.98	1.07	NA
50	31.1	0.63	0.49	0.45	1.00	1.07	NA
60	37.3	0.62	0.48	0.46	0.99	1.05	NA
70	43.5	0.59	0.48	0.47	0.89	0.92	NA
80	49.7	0.23	0.22	0.23	0.26	0.26	NA

Figure 7.3. Dynamic Friction Tester test results: October 20, 2021 (chart and data table)



Spring 2021: Post-snowplow		Dynamic Friction Result Average Friction Values (4 runs per test surface)					
Speed (km/h)	Speed (mph)	Control	GSB 8	GSB 6	Tac HFST	Baux HFST	New GSB
10	6.2	0.68	0.64	0.50	0.92	1.03	NA
20	12.4	0.66	0.60	0.48	0.91	1.01	NA
30	18.6	0.64	0.57	0.46	0.91	1.01	NA
40	24.9	0.62	0.54	0.44	0.90	1.00	NA
50	31.1	0.61	0.52	0.42	0.90	1.01	NA
60	37.3	0.60	0.51	0.41	0.90	1.00	NA
70	43.5	0.57	0.49	0.42	0.79	0.85	NA
80	49.7	0.21	0.16	0.14	0.18	0.21	NA

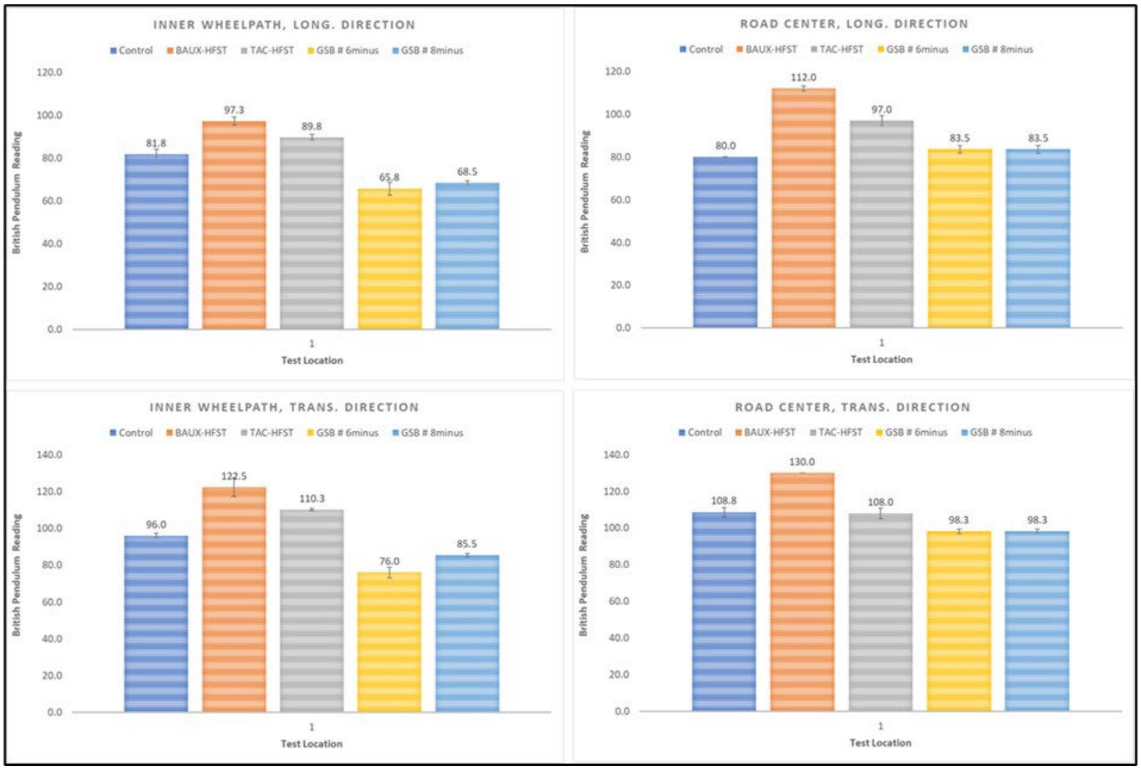
Figure 7.4. Dynamic Friction Tester test results: June 6, 2022 (chart and data table)



Spring 2022: Post-snowplow		Dynamic Friction Result Average Friction Values (4 runs per test surface)					
Speed (km/h)	Speed (mph)	Control	GSB 8	GSB 6	Tac HFST	Baux HFST	New GSB
10	6.2	0.65	0.66	0.55	0.87	1.00	NA
20	12.4	0.64	0.61	0.50	0.86	0.97	NA
30	18.6	0.63	0.59	0.47	0.85	0.96	NA
40	24.9	0.60	0.55	0.45	0.83	0.96	NA
50	31.1	0.58	0.54	0.44	0.83	0.96	NA
60	37.3	0.57	0.52	0.43	0.83	0.94	NA
70	43.5	0.54	0.50	0.41	0.74	0.81	NA
80	49.7	0.14	0.20	0.17	0.25	0.25	NA

The BP tests were also conducted four times per test section, with four replicates per test. Tests were conducted within the wheel path and outside of the wheel path (road center), in the longitudinal and transverse direction of traffic. Readings are taken parallel (longitudinal) and perpendicular (transverse) to the direction of traffic to measure potential influence of traffic on the orientation of aggregate particles. The BP data (Figure 7.5 to Figure 7.7) exhibit greater variability from test period to test period and even from pavement treatment to pavement treatment. This may in part be due to the nature of the test itself, for which readings are taken at a single point within each pavement section, as opposed to the larger footprint of the DFT and its ability to record values over a range of speeds in a single test.

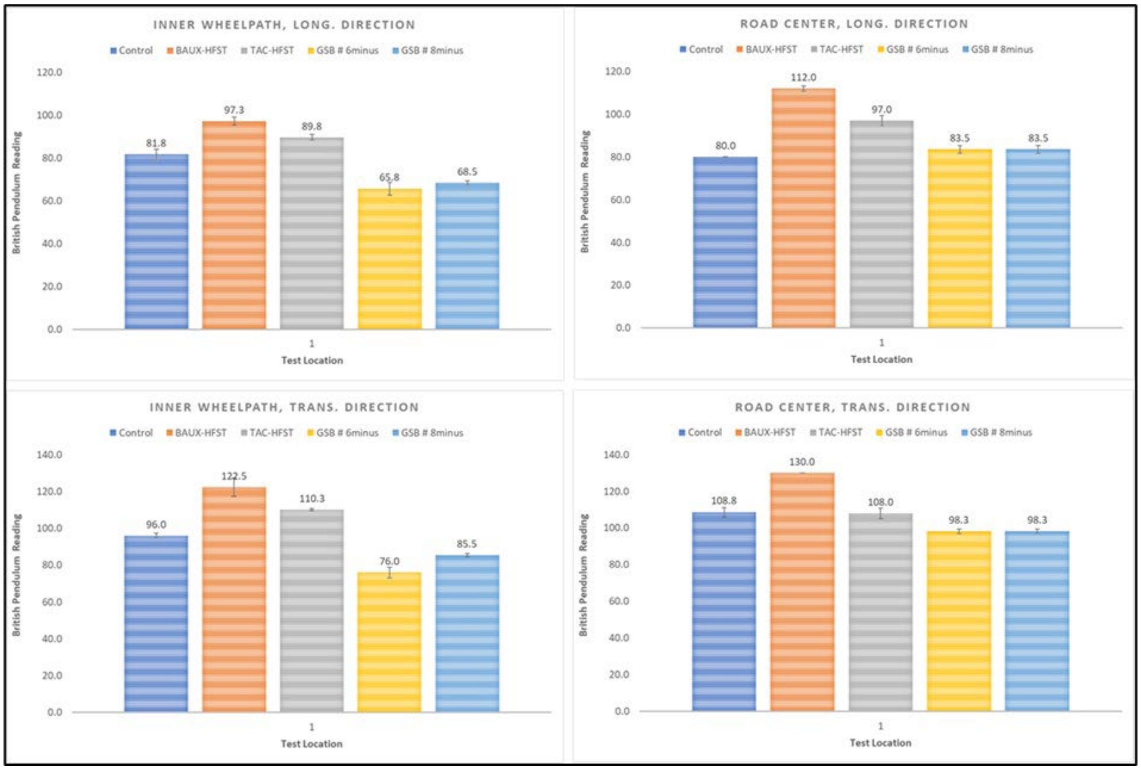
Figure 7.5. British Pendulum test results: August 5, 2021 (chart and data table)



Test section		Inner wheelpath		Road center	
		Long. Direction	Trans. Direction	Long. Direction	Trans. Direction
Control	1	85	95	80	105
	2	82	96	80	110
	3	80	98	80	110
	4	80	95	80	110
	Average	81.8	96.0	80.0	108.8
	Std. dev.	2.4	1.4	0.0	2.5
BAUX-HFST	1	97	120	111	130
	2	96	120	113	130
	3	100	130	113	130
	4	96	120	111	130
	Average	97.3	122.5	112.0	130.0
	Std. dev.	1.9	5.0	1.2	0.0
TAC-HFST	1	90	110	95	105
	2	90	110	95	106
	3	91	111	100	110
	4	88	110	98	111
	Average	89.8	110.3	97.0	108.0
	Std. dev.	1.3	0.5	2.4	2.9
GSB # 6minus	1	65	80	85	97
	2	64	76	82	98
	3	64	74	82	100
	4	70	74	85	98
	Average	65.8	76.0	83.5	98.3
	Std. dev.	2.9	2.8	1.7	1.3

Test section		Inner wheelpath		Road center	
		Long. Direction	Trans. Direction	Long. Direction	Trans. Direction
GSB # 8minus	1	68	85	85	97
	2	68	87	82	98
	3	68	85	82	100
	4	70	85	85	98
	Average	68.5	85.5	83.5	98.3
	Std. dev.	1.0	1.0	1.7	1.3

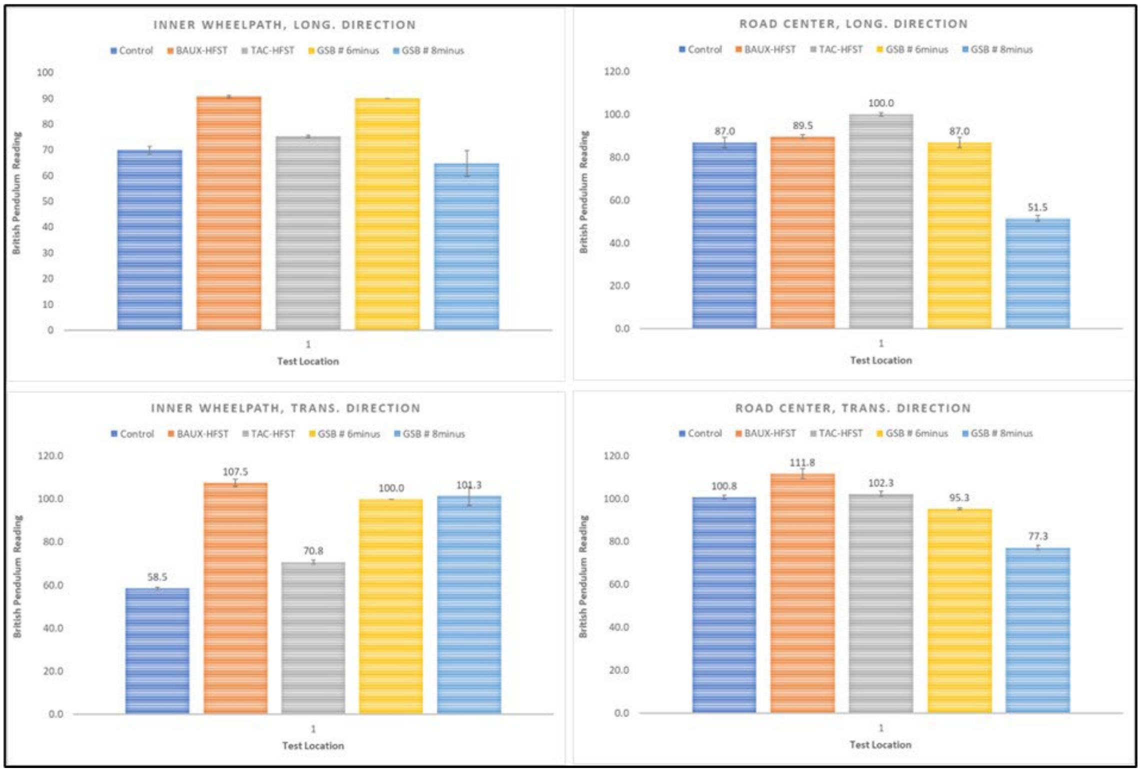
Figure 7.6. British Pendulum test results: October 21, 2021 (chart and data table)



Test section		Inner wheelpath		Road center	
		Long. Direction	Trans. Direction	Long. Direction	Trans. Direction
Control	1	85	65	95	115
	2	85	70	97	115
	3	85	65	95	115
	4	85	65	97	120
	Average	85.0	66.3	96.0	116.3
	Std. dev.	0.0	2.5	1.2	2.5
BAUX-HFST	1	132	105	110	95
	2	130	97	115	90
	3	130	100	110	90
	4	133	100	112	90
	Average	131.3	100.5	111.8	91.3
	Std. dev.	1.5	3.3	2.4	2.5
TAC-HFST	1	102	120	110	110
	2	100	120	105	105
	3	100	120	110	110
	4	102	120	110	110
	Average	101.0	120.0	108.8	108.8
	Std. dev.	1.2	0.0	2.5	2.5
GSB # 6minus	1	85	75	75	105
	2	95	75	75	105
	3	90	75	75	105
	4	88	77	76	105
	Average	89.5	75.5	75.3	105.0
	Std. dev.	4.2	1.0	0.5	0.0

Test section		Inner wheelpath		Road center	
		Long. Direction	Trans. Direction	Long. Direction	Trans. Direction
GSB # 8minus	1	65	60	80	45
	2	65	60	80	45
	3	68	60	80	45
	4	65	60	75	50
	Average	65.8	60.0	78.8	46.3
	Std. dev.	1.5	0.0	2.5	2.5

Figure 7.7. British Pendulum test results: June 6, 2022 (chart and data table)



Test section		Inner wheelpath		Road center	
		Long. Direction	Trans. Direction	Long. Direction	Trans. Direction
Control	1	68	58	90	100
	2	71	59	88	100
	3	70	59	85	102
	4	71	58	85	101
	Average	70.0	58.5	87.0	100.8
	Std. dev.	1.4	0.6	2.4	1.0
BAUX-HFST	1	90	109	90	115
	2	91	109	90	112
	3	91	106	90	110
	4	91	106	88	110
	Average	90.8	107.5	89.5	111.8
	Std. dev.	0.5	1.7	1.0	2.4
TAC-HFST	1	76	71	99	102
	2	75	70	100	104
	3	75	70	101	101
	4	75	72	100	102
	Average	75.3	70.8	100.0	102.3
	Std. dev.	0.5	1.0	0.8	1.3
GSB # 6minus	1	90	100	90	95
	2	90	100	88	95
	3	90	100	85	96
	4	90	100	85	95
	Average	90.0	100.0	87.0	95.3
	Std. dev.	0.0	0.0	2.4	0.5

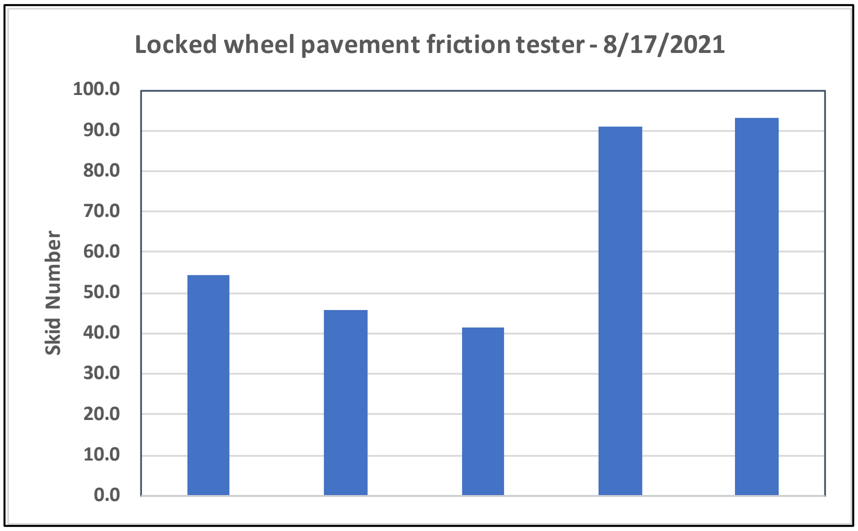
Test section		Inner wheelpath		Road center	
		Long. Direction	Trans. Direction	Long. Direction	Trans. Direction
GSB # 8minus	1	64	95	52	78
	2	58	102	53	76
	3	69	104	51	77
	4	68	104	50	78
	Average	64.8	101.3	51.5	77.3
	Std. dev.	5.0	4.3	1.3	1.0

The LWPFT was operated at a testing speed of 40 mph (64.4 kph), with five replicate tests conducted per pavement treatment section. When the vehicle's target speed of 40 mph (64.4 kph) was reached, a flow of water was deployed in advance of the friction testing trailer's left wheel, coincident with the locking of the left wheel. The deployment of water simulates braking on a wet pavement. Baseline test results from August 17, 2021, are summarized in Table 7.1 and Figure 7.8.

Table 7.1. Locked Wheel Pavement Friction Tester results: August 17, 2021

Section and Position		Run	Run	Run	Run	Run	Ave.
Control pavement	Left SN Average (Friction)	55.6	50.8	54.9	53.8	57.1	54.4
	Left SN Minimum (Friction)	49.2	44.3	50.3	43.5	53.4	48.1
	Left SN Maximum (Friction)	59.4	54.9	57.7	57.6	60.0	57.9
	Left SN Standard Deviation (Friction)	2.3	2.4	1.3	2.8	1.4	2.0
	Left SN Speed Average (mph)	40.1	40.0	40.4	40.2	40.1	40.2
	Left SN Flow Average (gpm)	0.0	0.0	0.0	0.0	0.0	0.0
GSB 88 -8	Left SN Average (Friction)	49.1	46.2	46.6	44.6	43.3	46.0
	Left SN Minimum (Friction)	45.3	43.2	42.3	41.6	40.2	42.5
	Left SN Maximum (Friction)	54.0	49.9	52.5	50.6	45.3	50.5
	Left SN Standard Deviation (Friction)	2.0	1.4	2.4	2.1	1.1	1.8
	Left SN Speed Average (mph)	39.6	39.9	39.9	39.8	40.2	39.9
	Left SN Flow Average (gpm)	0.0	0.0	0.0	0.0	0.0	0.0
GSB 88 -6	Left SN Average (Friction)	41.9	42.3	43.9	41.9	38.0	41.6
	Left SN Minimum (Friction)	35.2	37.0	39.1	38.7	34.5	36.9
	Left SN Maximum (Friction)	45.1	45.8	48.9	44.3	42.2	45.3
	Left SN Standard Deviation (Friction)	2.0	1.7	2.2	1.3	1.9	1.8
	Left SN Speed Average (mph)	40.8	40.7	41.0	41.0	41.3	41.0
	Left SN Flow Average (gpm)	0.0	0.0	0.0	0.0	0.0	0.0
Taconite HFST	Left SN Average (Friction)	109.4	88.9	89.7	91.7	93.2	90.9
	Left SN Minimum (Friction)	101.7	82.7	86.9	87.6	90.2	86.9
	Left SN Maximum (Friction)	117.4	93.8	94.2	95.0	96.7	94.9
	Left SN Standard Deviation (Friction)	3.8	1.9	1.7	1.4	1.4	1.6
	Left SN Speed Average (mph)	38.3	39.8	39.3	40.0	40.1	39.8
	Left SN Flow Average (gpm)	0.0	0.1	0.0	0.0	0.0	0.0
Bauxite HFST	Left SN Average (Friction)	92.6	93.5	93.2	93.7	93.3	93.3
	Left SN Minimum (Friction)	88.5	89.7	87.2	91.8	89.0	89.2
	Left SN Maximum (Friction)	97.1	97.0	100.1	96.7	96.9	97.6
	Left SN Standard Deviation (Friction)	1.9	1.7	3.1	1.3	1.5	1.9
	Left SN Speed Average (mph)	39.2	39.9	40.1	40.0	40.0	39.8
	Left SN Flow Average (gpm)	0.0	0.0	0.0	0.0	0.0	0.0

Figure 7.8. Locked Wheel Pavement Friction Tester results: August 17, 2021



The DFT results correlated well with the LWPFT results at the equivalent test speed of 40 mph (64.4 kph), as Figure 7.9 shows. Figure 7.10 is a plot of DFT results through June of 2022 at the equivalent LWPFT test speed.

Figure 7.9. Plot of Dynamic Friction Tester vs Locked Wheel Pavement Friction Tester results

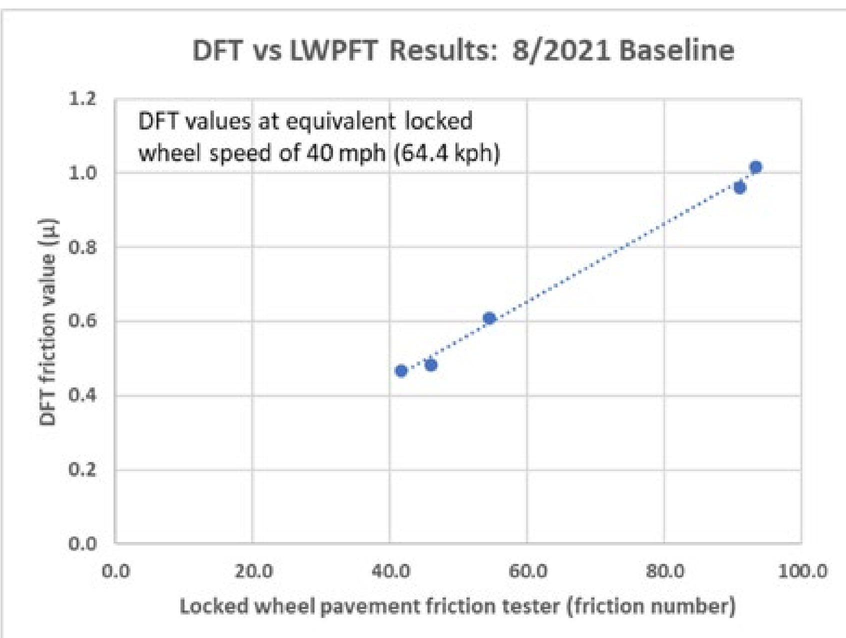
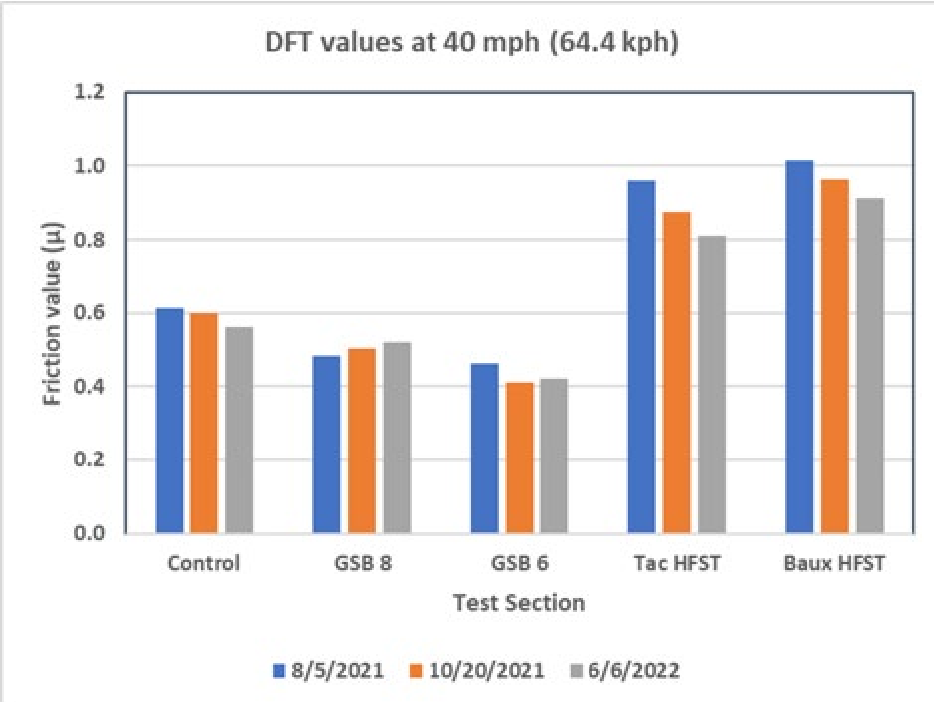


Figure 7.10. Dynamic Friction Tester results to date at equivalent LWPFT test speed of 40 mph (64.4 kph)

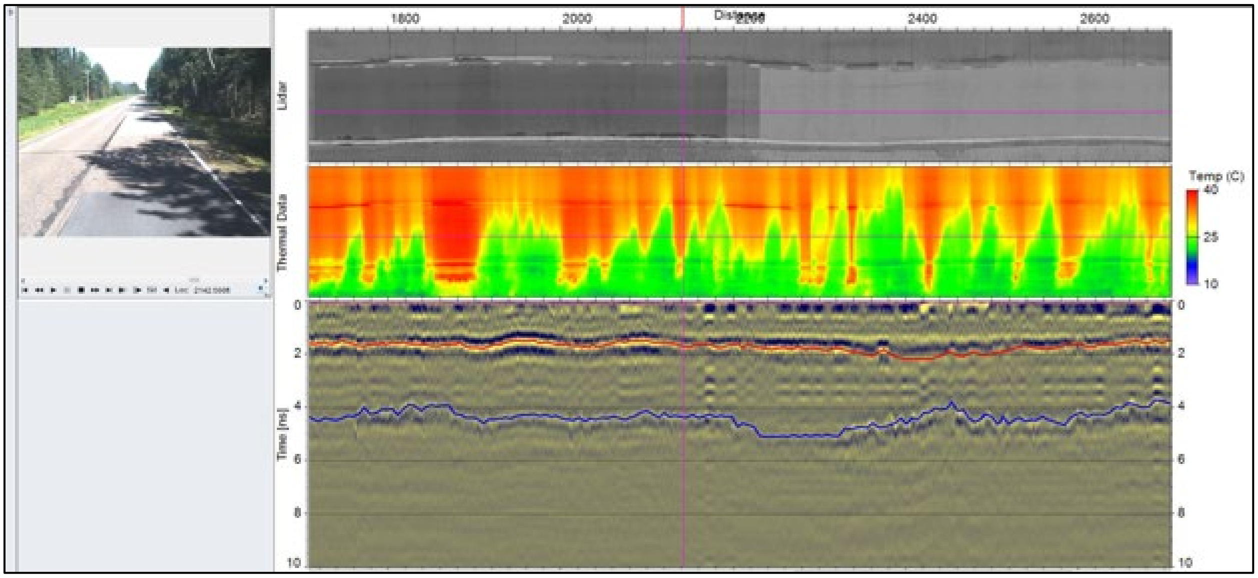


As previously noted, follow-up tests with MnDOT's Locked-Wheel Pavement Friction Tester were to take place during the 3rd quarter of 2022, shortly after the anticipated installation of the new GSB-based test section.

MnDOT's Road Doctor was deployed twice, on August 11, 2021, and November 3, 2021. As described and reported by Eyoab Zegeye, Senior Pavement Research Engineer, MnDOT, *"…the objective of this testing was to explore the possibility of measuring surface friction from the Lidar and accelerometer data collected using the Road Doctor Survey Van (RDSV). To analyze the data, an excellent report (Zuniga-Garcia and Prozzi, 2016) was relied on. Unfortunately, our analyses showed that our data is too coarse to be used for micro-texture studies that would provide surface friction characteristics. It may be possible to apply advanced resampling and filtering techniques to the data collected by the RDSV and extract characteristics related to surface friction. However, this will require the full attention of dedicated students with good numerical and computational backgrounds (may be an MS or Ph.D. student) looking for study topics."*

Figure 7.11 is a screenshot from the RDSV data analysis. While the RDSV data were not useable for discerning micro-texture, the thermal data suggests the darker taconite HFST section (left half of image) has a more intense temperature signature than the lighter bauxite HFST section (right half of image). Also note the effect of tree shadows on pavement temperature ("cooler" green colors). The ability of a pavement to absorb energy (and therefore heat) more readily from the sun could be a helpful attribute for more efficient and effective deicing during the winter.

Figure 7.11. Screenshot of Road Doctor Survey Van (RDSV) data, showing taconite and bauxite HFST sections from left to right



A potential test would be to use the Road Doctor to collect thermal data when the sun is directly aligned with the road, which runs north south, to eliminate shadowing from the trees, in both the summer and winter. This way, a complete thermal profile could be obtained for each test section.

7.2.2 Pavement condition documentation and sampling

On February 25, 2022, the PI visited the project site and noted significant distress in the bauxite HFST section (Figure 7.12). It was speculated that – when combined with pre-existing weaknesses in the underlying chip sealed asphalt pavement (note the salt residue coincidental with the cracking in the adjacent southbound lane shown in Figure 7.13) – the epoxy bond was so strong that as a snowplow's blade passed over the very high friction bauxite aggregate, the blade was "grabbed", and the pulling/shear force exceeded the bond strength between the chipseal and the weaker pavement below. The failure also roughly coincided with the wheel path. Importantly, the HFST epoxy had *not* delaminated from the chipseal; rather, the chipseal had pulled completely away from the underlying asphalt pavement, exposing it as shown in Figure 7.14. The taconite HFST section exhibited similar (but less) distress.

Figure 7.12. February 25, 2022, photo of distresses/losses in bauxite HFST test section

Figure 7.13. Photo showing potential relationship of pre-existing pavement cracking in "Control" pavement (left) to the losses in the HFST test section (right)

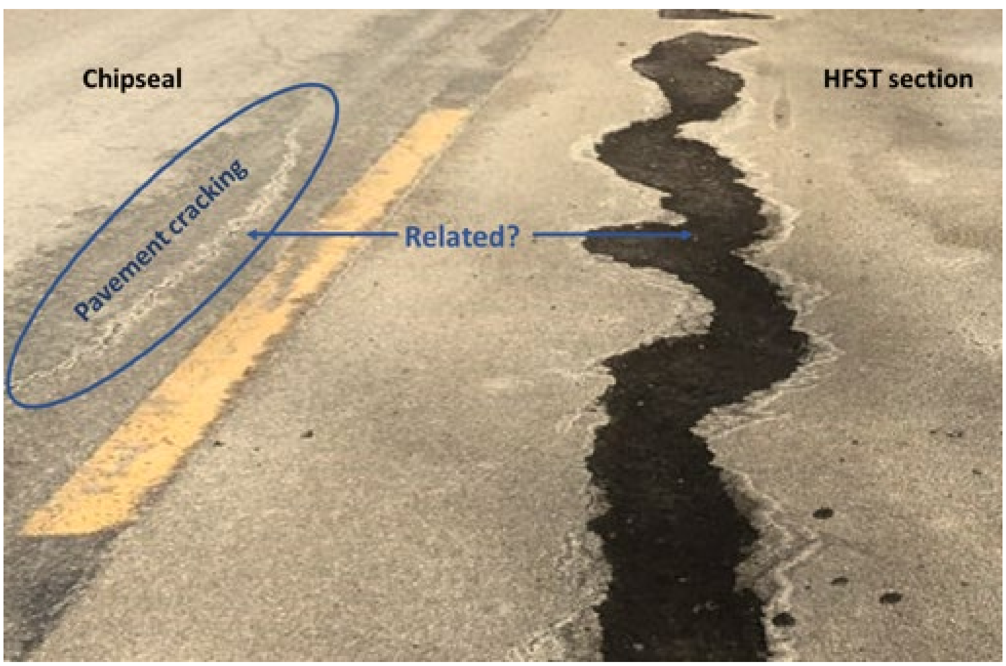
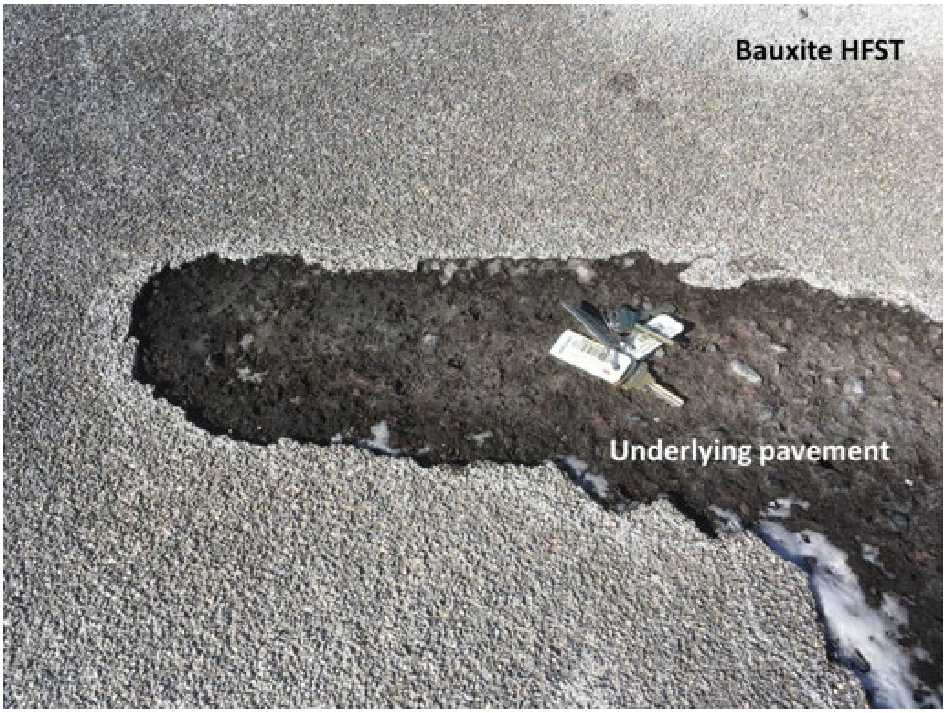


Figure 7.14. Photo showing complete exposure of underlying pavement where HFST loss occurred in the bauxite test section



A meeting between the project's PI, TL, and St. Louis County TAP representative at the time (Victor Lund) took place on March 7, 2022, to discuss these pavement distresses. Micro-milling the existing chipseal prior to the HFST installations had originally been planned, but the contractor said micro-milling was unnecessary based on their prior experience. Whether the decision not to micro-mill contributed to the distresses is uncertain. However, it was recommended that an analysis of failure be conducted to help identify the cause, including collecting cores of selected portions of the pavement. This analysis of failure began on June 6, 2022, during the project's third set of friction tests, and continued during a follow-up site visit on July 5.

On June 6, 2022, the HFST distresses showed little to no additional development from their February 25 state, even after an extended snow plowing season that ended in early May of 2022. This suggested the failures were probably related to (and exacerbated by) preexisting weaknesses in the underlying chip sealed pavement, making the pavement more susceptible to moisture infiltration and localized dilation (bulging?) caused by freezing early in the winter 2021-22 season and easier to "pluck" by snow plowing. Cores (Figure 7.15 and Figure 7.16) were collected by St. Louis County personnel and underwent further examination. Figure 7.17 is a close-up of a bauxite HFST core, showing the relative thicknesses of the HFST and underlying chipseal treatment. The HFST (epoxy/resin and aggregate) is about 3 to 4 mm thick; the chipseal layer is about 5 to 6 mm thick. In contrast, cores from the two GSB-based sections show the thinner nature of the treatment. Following coring, all holes were filled with the NRRI's rapid-setting repair compound (Figure 7.18); each achieved a drivable set in about 10 minutes.

Figure 7.15. Collection of sample cores by St. Louis County personnel (left) and cored pavement (right)

Figure 7.16. Cores collected from the four pavement treatment test sections

Figure 7.17. Close-up photo of bauxite HFST core, showing the relative thicknesses of the HFST and underlying chipseal treatment

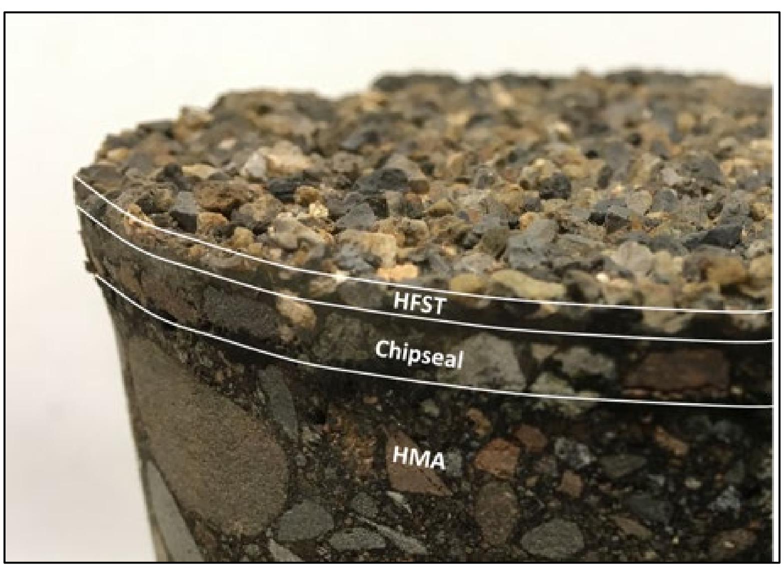
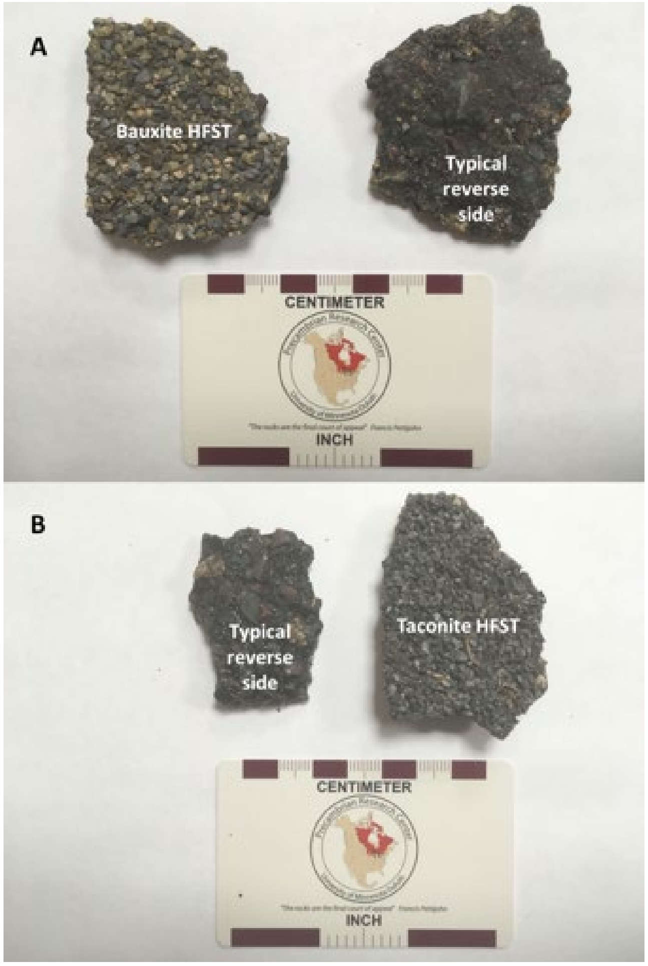


Figure 7.18. Core hole filled with the NRRI's rapid-setting repair compound

As a follow-up, an additional site visit took place on Tuesday, July 5, 2022, to further study and document the HFST distresses. Fragments of snowplow "plucked" bauxite (Figure 7.19) and taconite HFSTs were found scattered along the shoulder, and several fragments were collected for closer examination (Figure 7.20). Their reverse side appearance, as well as that of the underlying pavement, suggest two mechanisms of failure: 1) at the interface between the chipseal and underlying HMA; and 2) within the HMA itself. Notably, the bond *between* the HFST and chipseal did not show any evidence of failure.

Figure 7.19. Photo of bauxite HFST fragments collected on July 5, 2022

Figure 7.20. Representative fragments of snowplow "plucked" bauxite (A) and taconite (B) HFST



The bauxite HFST section installed for St. Louis County in 2020 (at the horizontal curve just to the south of the current project's test sections) was also examined on July 5. It exhibited similar distresses/losses (Figure 7.21) that were not noticed on February 25, 2022. Prior to this 2020 HFST installation, the existing chipseal *had* been micro-milled. Note that in Figure 7.21B, the faint cracks in the HFST coincide with and extend beyond the distress/loss (circled). This is another indication of a pre-existing condition (physical weakness) in the underlying pavement contributing to loss of HFST via reflective cracking.

Figure 7.21. July 5, 2022, photos of losses in bauxite HFST installed in 2020: Looking south toward horizontal curve (A); closer view of HFST loss and visible faint cracks (B, circled); and close-up of underlying exposed asphalt pavement (C)

7.3 Testing phase of the project

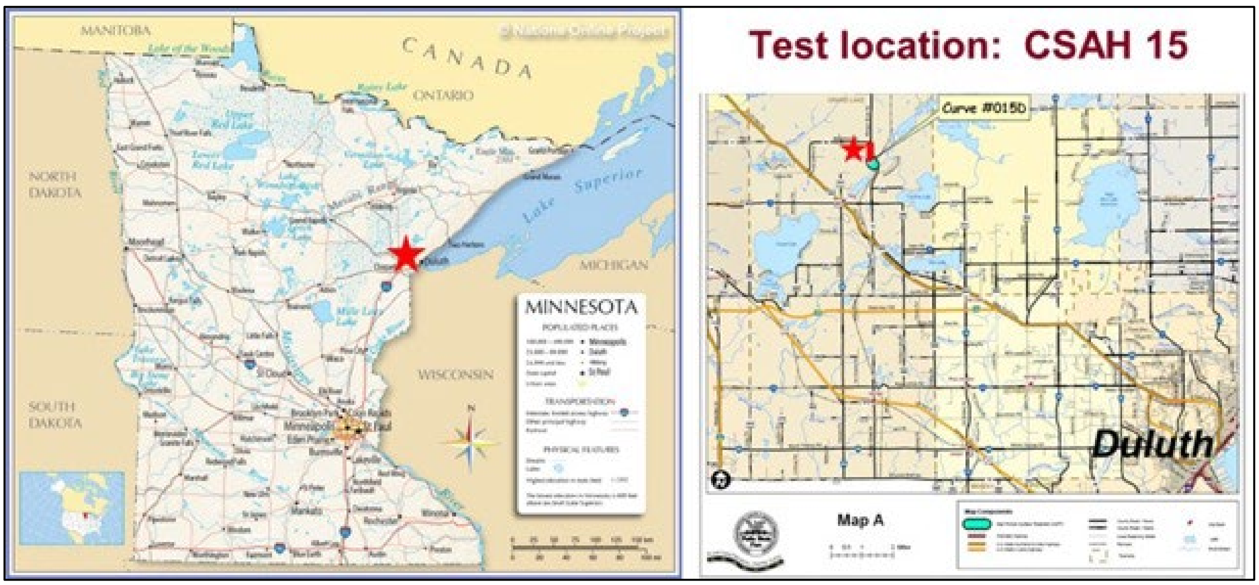
This phase represented the final pavement test section monitoring and testing phase of the project (i.e., August 2022 to May 2025), and was a continuation of previous Year 1 testing. Field monitoring of installed systems and field performance tracking and testing continued twice per year, using the same equipment: DFT, BPT, and LWPFT. A demonstration of a Sideway-force Coefficient Routine Investigation Machine (SCRIM) technology was arranged by the project team and took place on July 26th of 2024. A cradle-to-gate life cycle assessment (LCA) of Taconite and Bauxite HFST systems was also performed.

The activities were coordinated by the former Principal Investigator (PI) and current project consultant and co-Investigator, Larry Zanko, with: St. Louis County Traffic Engineer and project Technical Liaison (TL), Victor Lund, and Project Coordinator (PC), Jackie Jiran (MnDOT); South Sign Supervisor for St. Louis County Public Works, Dwain Ecklund (traffic control); the project's current Principal Investigator, Professor Mihai Marasteanu (UMTC) and co-Investigator, Professor Manik Barman (UMD); Mugurel Turos (UMTC); and MnDOT's Christopher Nadeau and Gregory Larson. Additional project support was provided by Sara Post, P.E., and Matt Aro of the Natural Resources Research Institute (NRRI, UMD).

7.3.1 Test sections

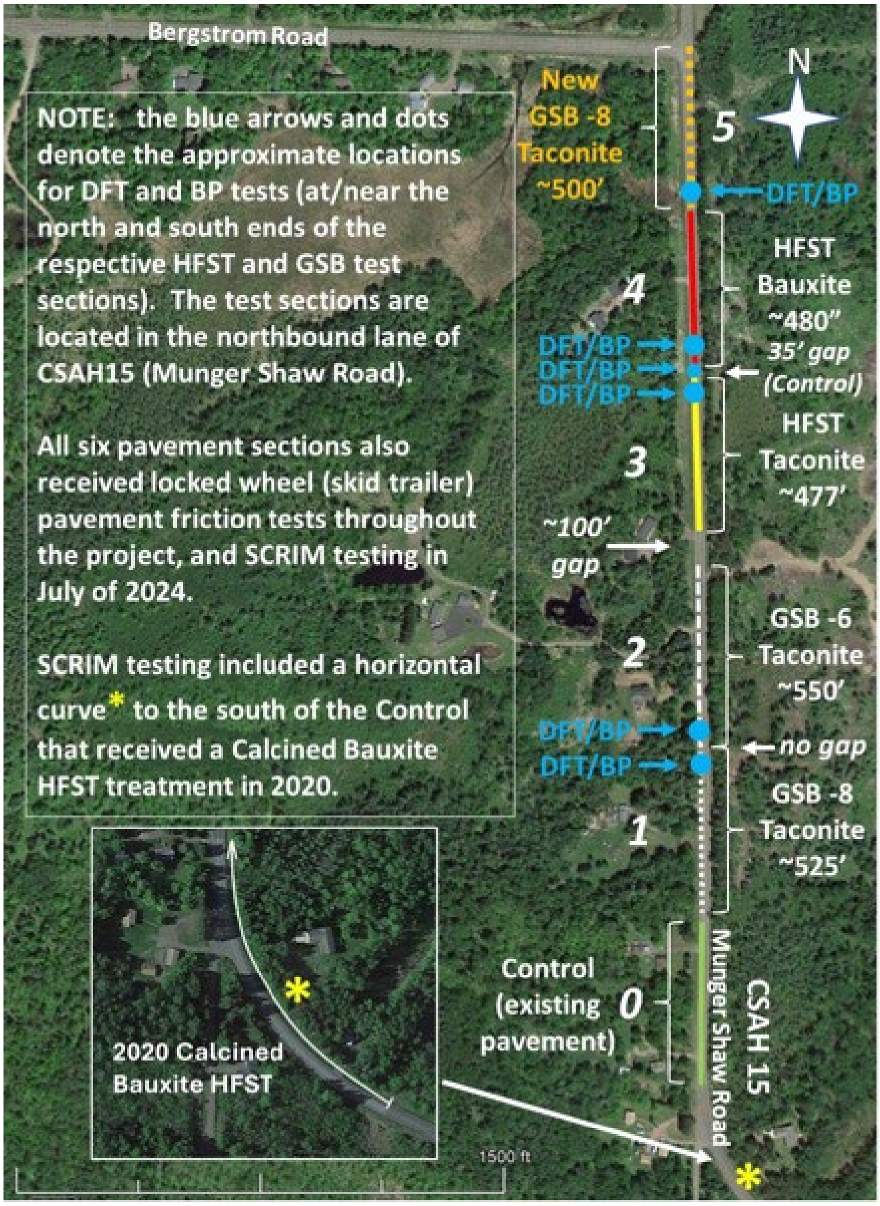
The project test site is located on CSAH-15, approximately 12 miles northwest of Duluth, MN (Figure 7.22).

Figure 7.22. Project location map



Four surface-treated pavement test sections were installed on July 29, 2021, as described in chapter 5. A fifth test section was added in 2022. In addition to a control (Test Section 0, i.e., the existing chip sealed pavement), the surface-treated test sections consist of the following, as shown from south to north in Figure 7.23:

Figure 7.23. Project location map showing Control (0) and pavement surface treatment test sections 1 to 5, DFT and BP testing locations, and horizontal curve #015D included in the July 2024 SCRIM testing (*inset)



- **Test Section 0** Control (Existing chip sealed pavement)
- **Test Section 1** Taconite applied using a standard gradation GSB-based system (GSB -8)
- **Test Section 2** Taconite applied using a GSB-based system at a slightly coarser gradation than Test 1 (GSB -6)
- **Test Section 3** Taconite applied with epoxy/resin – Typical HFST installation (HFST Tac)
- **Test Section 4** Bauxite applied with epoxy/resin – Typical HFST installation (HFST Baux)
- **Test Section 5** Taconite applied using a standard gradation GSB-based system (New GSB -8), but at a higher aggregate application rate

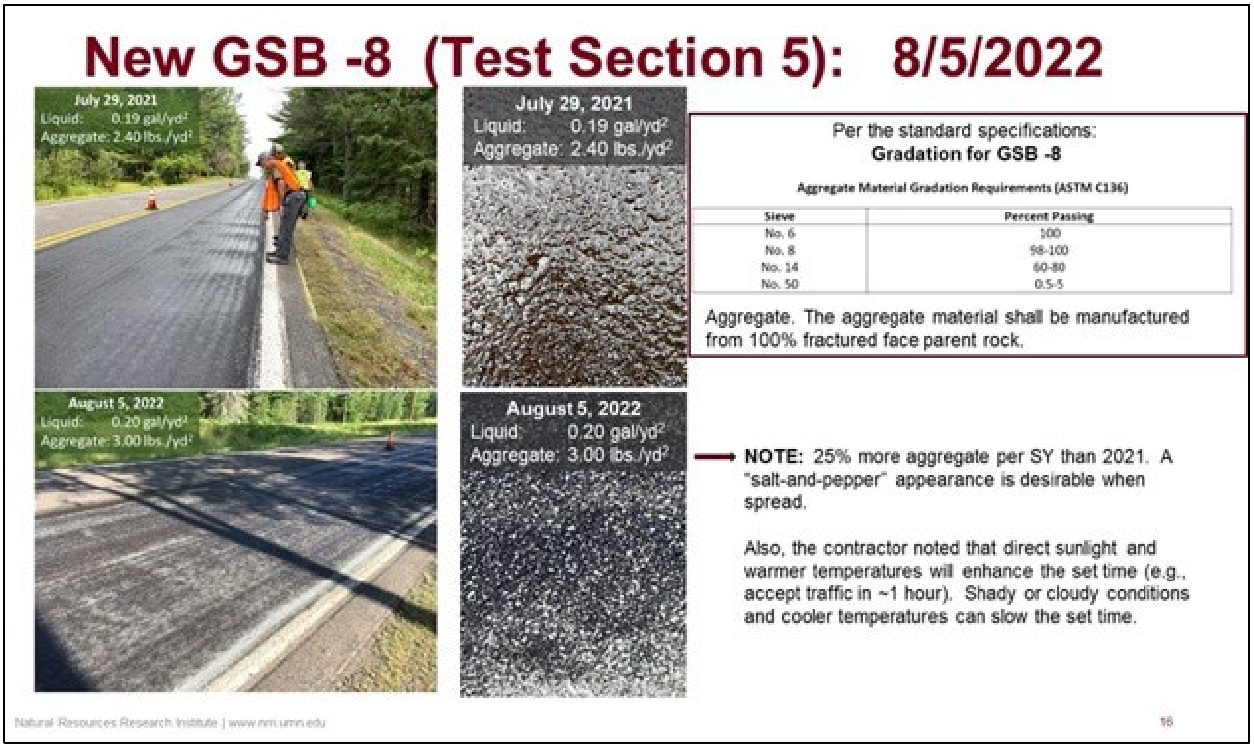
Also shown in Figure 7.23 are the DFT and BP testing locations that were used throughout the project. Note that the DFT and BP tests for the Control took place on an untreated 35' (~10 m) gap of existing chip sealed pavement between Taconite and Bauxite HFST Test Sections 3 and 4. The LWPFT and SCRIM tests were conducted over the full-length Control interval at the project's south end (Test Section 0), with the SCRIM test including a horizontal curve (#015D) immediately to the south that received a calcined bauxite HFST treatment in 2020 (Figure 7.23 inset).

Testing performed during the first year of the project showed that the two GSB-based test sections (Test Sections 1 and 2) had friction numbers lower than the chipseal Control. As described previously, follow-up discussions indicated that a calibration issue with the deployment equipment possibly led to an aggregate application rate that was too low relative to the liquid emulsion application rate. As a result, the GSB-based system contractor coordinated with the friction aggregate provider, the PI, and St. Louis County, and added a new test section **(Test Section 5)** on August 5, 2022, at no cost to the project, again using -8 taconite aggregate (i.e., 98 to 100% passing a No. 8 sieve), but applying 25% more aggregate per square yard than what had been applied during the installation of Test Sections 1 and 2.

Figure 7.24 and Figure 7.25 show, respectively, August 5, 2022, Test Section 5 deployment and its updated liquid and aggregate application rate.

Figure 7.24. Installation of new GSB -8 (Test Section 5) on August 5, 2022

Figure 7.25. Liquid and aggregate application rate of new (2022) GSB-taconite test section compared to 2021 GSB-taconite test section



7.4 Post-installation follow-up testing (September 2022 to MAY 2025)

Test segment condition monitoring, documentation, skid resistance testing, field performance tracking, and conference presentations comprised the project's second phase (Years 2 to 4+). Collection and study of a second set of pavement cores also took place in May of 2025 to assess aggregate wear characteristics.

7.4.1 Friction testing methods

Pavement testing continued through the Spring of 2025 using the DFT, BPT, and LWPFT, and also WDM USA's SCRIM in July of 2024. Figure 7.26 shows each testing device and describes their respective operating parameters. The SCRIM is a full-size, over-the-road vehicle, which can perform and provide the following tests and data (https://www.wdm-int.com/images/uploads/content/SCRIM_US_brochure_2022.pdf):

- Single-or double-wheel path friction and texture measurement
- GPS-linked friction, texture, roughness (IRI), geometric, and video data
- Dynamic vertical load and water flow control, air and surface temperature measurement
- Continuous data collection between 15 and 55 mph (24 and 89 km/h)

Figure 7.26. Data collection methods/equipment and respective operating parameters: A) Dynamic Friction Tester; B) British Pendulum; C) MnDOT's Locked-Wheel Pavement Friction Tester; and D) Sideway-force Coefficient Routine Investigation Machine (SCRIM)

A. Dynamic Friction Tester (ASTM : E-1911-98)
0 to 80 km/h (0 to 50 mph)
142 mm (5.6") measurement radius

B. British Pendulum device (ASTM E303)
~10 km/h (~ 6 mph)
Small footprint (centimeters^2)

C. Locked-wheel pavement friction tester
64.4 km/h (40 mph)
~30m (100') minimum pavement interval

D. Sideway-force Coefficient Routine Investigation Machine (SCRIM)
24 to 88.5 km/h (15 to 55 mph)
Continuous data collection over several kilometers / miles

As usual, St. Louis County provided traffic control for DFT and BP testing (Figure 7.27). To maximize safety, all DFT and BP testing took place in the right half of the northbound lane (i.e., in the wheel path closest to the fog line) and between wheel paths in the center of the northbound lane). The project's final set of post-snowplowing DFT, BP, and LWPFT tests took place in Spring of 2025.

Figure 7.27. Typical DFT and BP setup, with traffic control

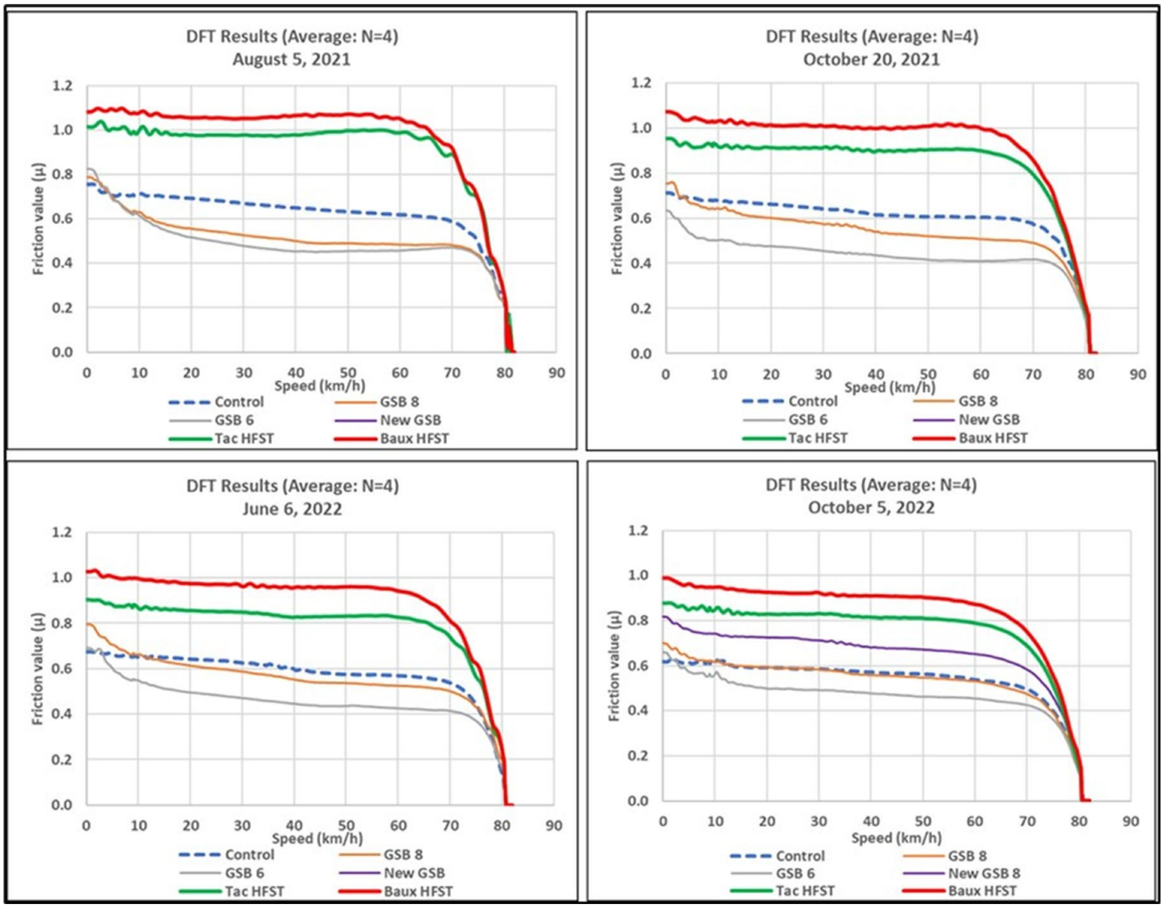
The DFT data were collected, compiled, and summarized by Mugurel Turos, UMTC, while the BP data were collected, compiled, and summarized by project co-investigator Prof. Manik Barman, UMD; both received assistance from UMTC and UMD students, respectively. LWPFT data were collected and provided by MnDOT's Christopher Nadeau. The SCRIM data, collected by WDM during its July 26, 2024, demonstration, was reported to the project team by WDM's Ryland Potter and Isaac Briskin.

7.4.2 Friction Testing Results

7.4.2.1 Dynamic Friction Tester (DFT) results through Spring of 2025

The DFT tests were conducted within the wheel path of each test section – typically four replicates per test section – with the DFT device repositioned after each test to provide a more representative composite result. The DFT data for the entire project are presented in Figure 7.28, Figure 7.29, and Figure 7.30, with average friction values, from 0 to 80 km/h, plotted for each pavement test section; corresponding numeric data in 10 km/h increments are presented in tabular form below each plot. Figure 7.30 represents the project's final (May 5, 2025) DFT measurements compared to each test section's baseline values. Figure 7.31 shows, in histogram form, friction values for all nine wheel-path DFT tests conducted during the project, at the equivalent speed of the locked wheel pavement friction tester, i.e., 40 mph (64.4 km/h).

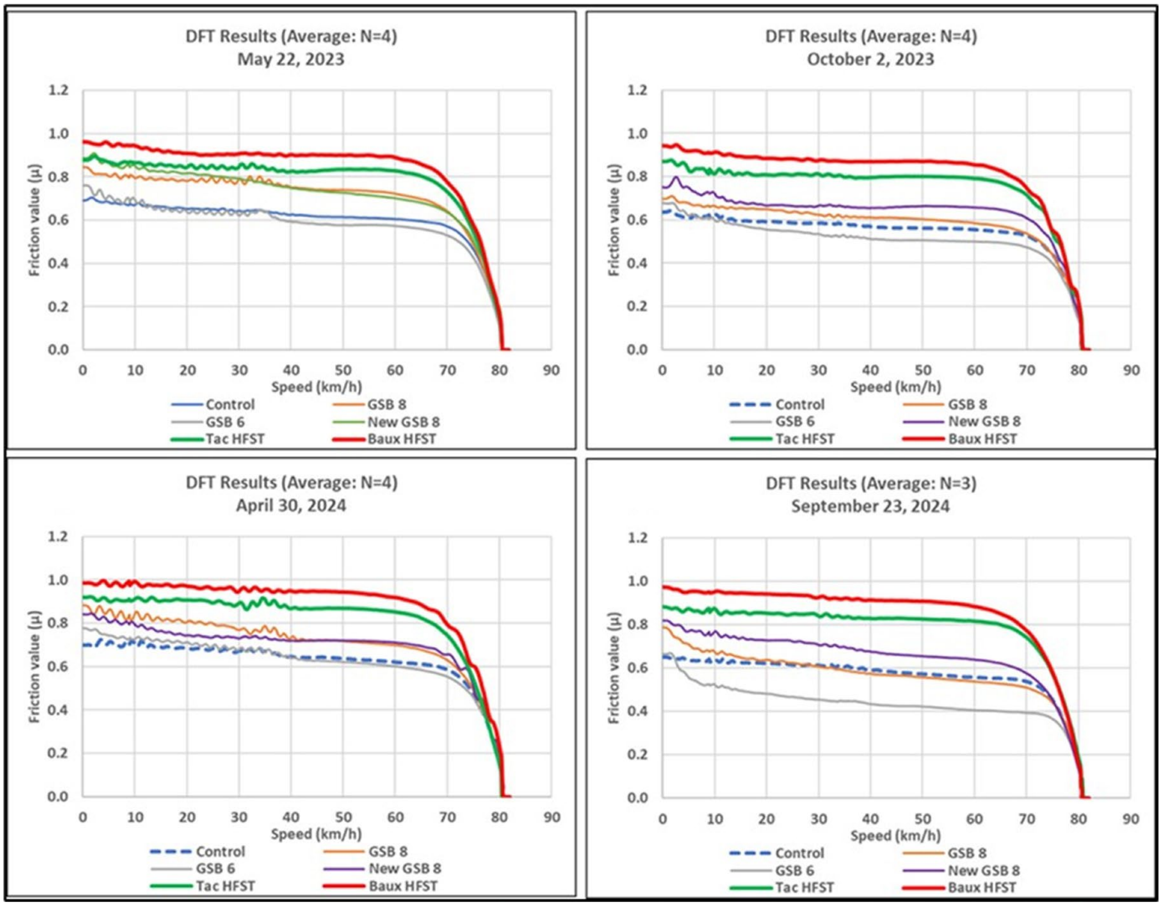
Figure 7.28. Dynamic Friction Tester test results: August 5, 2021, through October 5, 2022 (charts and data table)



Test time	Speed (km/h)	Speed (mph)	Average Friction Values (4 runs per test surface)					
			Control	GSB 8	GSB 6	Tac HFST	Baux HFST	New GSB
Aug.5 2021 Baseline	10	6.2	0.71	0.63	0.62	1.00	1.08	NA
	20	12.4	0.69	0.56	0.52	0.98	1.06	NA
	30	18.6	0.67	0.53	0.48	0.98	1.05	NA
	40	24.9	0.65	0.50	0.45	0.98	1.07	NA
	50	31.1	0.63	0.49	0.45	1.00	1.07	NA
	60	37.3	0.62	0.48	0.46	0.99	1.05	NA
	70	43.5	0.59	0.48	0.47	0.89	0.92	NA
	80	49.7	0.23	0.22	0.23	0.26	0.26	NA
Oct.20 2021 Pre-snowplow	10	6.2	0.68	0.64	0.50	0.92	1.03	NA
	20	12.4	0.66	0.60	0.48	0.91	1.01	NA
	30	18.6	0.64	0.57	0.46	0.91	1.01	NA
	40	24.9	0.62	0.54	0.44	0.90	1.00	NA
	50	31.1	0.61	0.52	0.42	0.90	1.01	NA
	60	37.3	0.60	0.51	0.41	0.90	1.00	NA
	70	43.5	0.57	0.49	0.42	0.79	0.85	NA
	80	49.7	0.21	0.16	0.14	0.18	0.21	NA

Test time	Speed (km/h)	Speed (mph)	Average Friction Values (4 runs per test surface)					
			Control	GSB 8	GSB 6	Tac HFST	Baux HFST	New GSB
Jun.6 2022 Post-snowplow	10	6.2	0.65	0.66	0.55	0.87	1.00	NA
	20	12.4	0.64	0.61	0.50	0.86	0.97	NA
	30	18.6	0.63	0.59	0.47	0.85	0.96	NA
	40	24.9	0.60	0.55	0.45	0.83	0.96	NA
	50	31.1	0.58	0.54	0.44	0.83	0.96	NA
	60	37.3	0.57	0.52	0.43	0.83	0.94	NA
	70	43.5	0.54	0.50	0.41	0.74	0.81	NA
	80	49.7	0.14	0.20	0.17	0.25	0.25	NA
Oct.5 2022 Pre-snowplow	10	6.2	0.62	0.62	0.56	0.85	0.95	0.74
	20	12.4	0.59	0.59	0.50	0.83	0.93	0.72
	30	18.6	0.58	0.58	0.49	0.83	0.92	0.71
	40	24.9	0.57	0.56	0.48	0.82	0.91	0.68
	50	31.1	0.56	0.55	0.46	0.81	0.90	0.67
	60	37.3	0.54	0.53	0.45	0.79	0.87	0.65
	70	43.5	0.50	0.48	0.42	0.69	0.75	0.58
	80	49.7	0.13	0.13	0.12	0.15	0.19	0.17

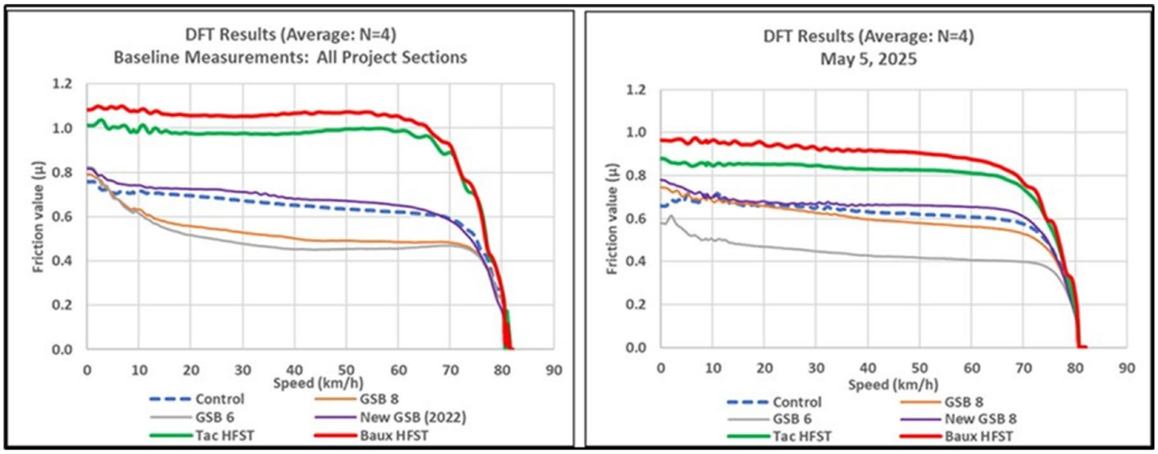
Figure 7.29. Dynamic Friction Tester test results: May 22, 2023, through September 23, 2024 (charts and data table)



Test time	Speed (km/h)	Speed (mph)	Average Friction Values (4 runs per test surface)					
			Control	GSB 8	GSB 6	Tac HFST	Baux HFST	New GSB
May. 22 2023 Post-snowplow	10	6.2	0.67	0.80	0.70	0.87	0.94	0.85
	20	12.4	0.65	0.78	0.64	0.85	0.91	0.82
	30	18.6	0.64	0.79	0.62	0.85	0.91	0.79
	40	24.9	0.63	0.75	0.60	0.83	0.90	0.75
	50	31.1	0.61	0.74	0.58	0.84	0.90	0.73
	60	37.3	0.61	0.72	0.57	0.83	0.89	0.70
	70	43.5	0.57	0.64	0.53	0.73	0.78	0.64
	80	49.7	0.14	0.15	0.12	0.17	0.18	0.20
Oct.2 2023 Pre-snowplow	10	6.2	0.62	0.66	0.60	0.81	0.91	0.72
	20	12.4	0.59	0.65	0.55	0.81	0.88	0.67
	30	18.6	0.58	0.62	0.53	0.81	0.88	0.67
	40	24.9	0.57	0.61	0.51	0.80	0.87	0.66
	50	31.1	0.56	0.60	0.51	0.80	0.87	0.67
	60	37.3	0.55	0.58	0.50	0.79	0.85	0.66
	70	43.5	0.52	0.54	0.47	0.71	0.75	0.61
	80	49.7	0.15	0.16	0.13	0.21	0.21	0.16

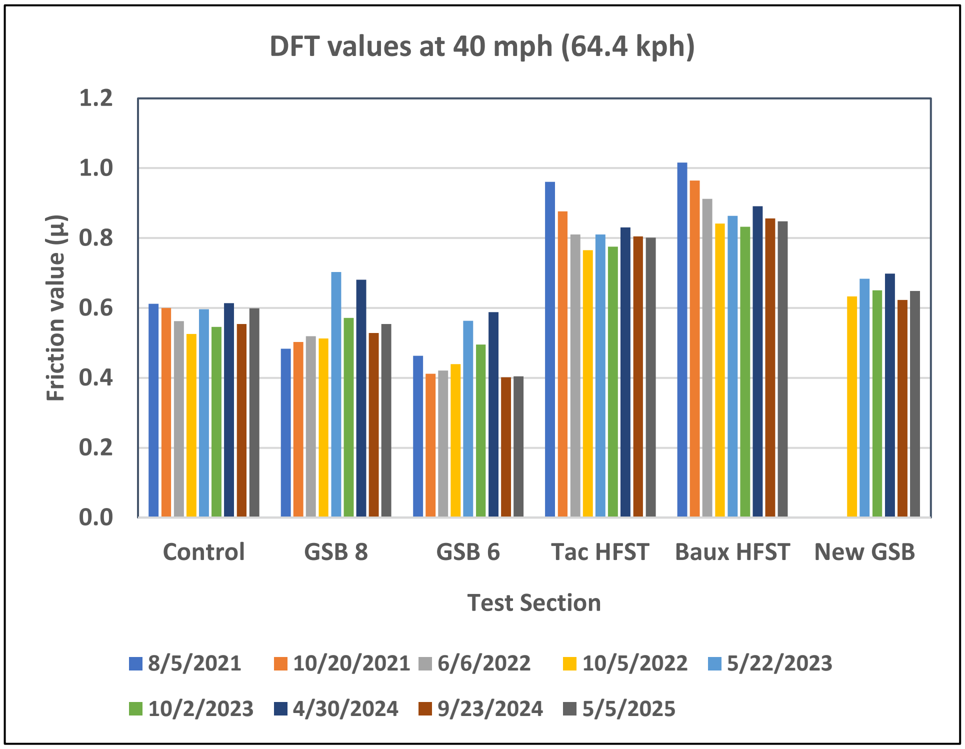
Test time	Speed (km/h)	Speed (mph)	Average Friction Values (4 runs per test surface)					
			Control	GSB 8	GSB 6	Tac HFST	Baux HFST	New GSB
Apr.30 2024 Post-snowplow	10	6.2	0.70	0.84	0.73	0.91	0.99	0.79
	20	12.4	0.69	0.80	0.71	0.91	0.97	0.75
	30	18.6	0.67	0.77	0.68	0.89	0.95	0.73
	40	24.9	0.65	0.73	0.64	0.87	0.95	0.72
	50	31.1	0.64	0.72	0.62	0.87	0.94	0.72
	60	37.3	0.62	0.70	0.60	0.85	0.92	0.71
	70	43.5	0.59	0.63	0.55	0.74	0.79	0.66
	80	49.7	0.16	0.17	0.19	0.15	0.24	0.19
Sep.23 2024 Pre-snowplow	10	6.2	0.64	0.67	0.52	0.87	0.95	0.77
	20	12.4	0.62	0.64	0.48	0.85	0.94	0.73
	30	18.6	0.61	0.61	0.45	0.84	0.93	0.70
	40	24.9	0.59	0.57	0.43	0.83	0.91	0.67
	50	31.1	0.57	0.56	0.42	0.83	0.91	0.65
	60	37.3	0.56	0.54	0.41	0.82	0.88	0.64
	70	43.5	0.54	0.51	0.39	0.74	0.77	0.57
	80	49.7	0.15	0.17	0.15	0.19	0.16	0.14

Figure 7.30. Dynamic Friction Tester test results: Baseline (2021 and 2022) and Final (May 2025) (charts and data table)



Test time	Speed (km/h)	Speed (mph)	Average Friction Values (4 runs per test surface)					
			Control	GSB 8	GSB 6	Tac HFST	Baux HFST	New GSB
Aug.5 2021 & Oct.5 2022 Baseline	10	6.2	0.71	0.63	0.62	1.00	1.08	0.74
	20	12.4	0.69	0.56	0.52	0.98	1.06	0.72
	30	18.6	0.67	0.53	0.48	0.98	1.05	0.71
	40	24.9	0.65	0.50	0.45	0.98	1.07	0.68
	50	31.1	0.63	0.49	0.45	1.00	1.07	0.67
	60	37.3	0.62	0.48	0.46	0.99	1.05	0.65
	70	43.5	0.59	0.48	0.47	0.89	0.92	0.58
	80	49.7	0.23	0.22	0.23	0.26	0.26	0.17
May.5 2023 Post-snowplow	10	6.2	0.70	0.68	0.50	0.85	0.96	0.70
	20	12.4	0.66	0.66	0.47	0.85	0.94	0.68
	30	18.6	0.65	0.63	0.45	0.85	0.93	0.67
	40	24.9	0.63	0.60	0.43	0.83	0.92	0.67
	50	31.1	0.62	0.58	0.42	0.83	0.90	0.66
	60	37.3	0.61	0.56	0.41	0.81	0.87	0.65
	70	43.5	0.57	0.53	0.40	0.74	0.76	0.61
	80	49.7	0.17	0.15	0.15	0.18	0.24	0.15

Figure 7.31. Histogram comparison of friction values determined by DFT for all tests sections at 40 mph (64.4 km/h) equivalent

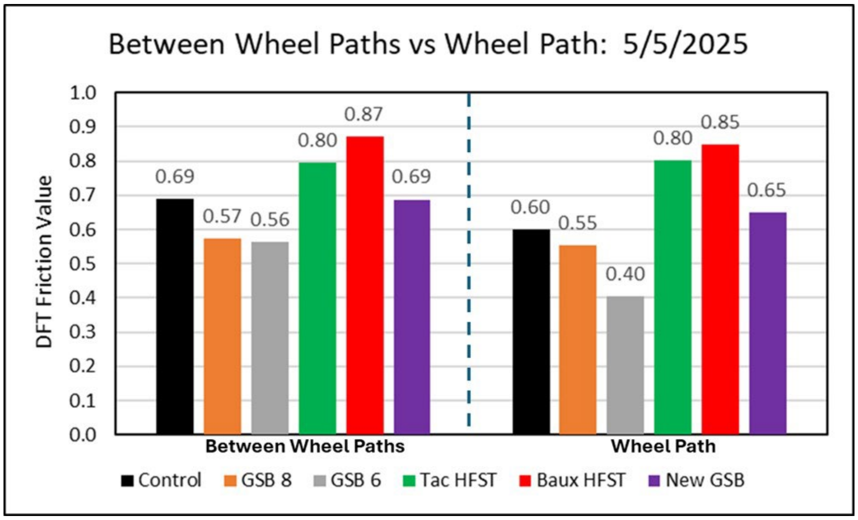


To provide a "non-trafficked" data point for comparison of wear, a single DFT test was conducted between the wheel paths of each test section for the May 22, 2023, through May 5, 2025, testing period. The initial August 5, 2021, test results are assumed to provide the equivalent of baseline friction values between wheel paths values for GSB 8, GSB 6, Tac HFST, and Baux HFST sections; similarly, the initial October 2, 2022, test results provide an equivalent baseline value for the New GSB 8 section. **NOTE: Because *this data comparison is based on only a single measurement made between wheel paths, per field testing date, the following results should be viewed with this in mind as being illustrative of the wear differential.***

Figure 7.32 presents the comparative results in combined graphical (A) and tabular (B and C) form, and it shows that post-installation wheel path friction values are lower than friction values between wheel paths. Histogram (A) illustrates the final (May 5, 2025) DFT results at the equivalent speed of the locked wheel pavement friction tester, i.e., 40 mph (64.4 km/h). Tabular (B) shows friction values for field testing dates for which wheel path and between wheel paths data were collected. Tabular (C) shows by what percentage the May 5, 2025, wheel path friction values were lower than between wheel paths values (C-i); and by what percentage the May 5, 2025, wheel path friction values were lower than initial (baseline) values (C-ii). As C-i shows, the wheel path and between wheel paths friction differential is relatively small for the Tac HFST, Baux HFST, and GSB 8 and New GSB test sections, larger for the Control, and largest for the problematic GSB 6 test section (whose aggregate-to-liquid emulsion ratio was too low). The larger friction differential for the Control can be explained by it being older than the project's test sections; therefore, its wheel paths experienced a longer period of traffic wear.

Interestingly, the May 5, 2025, vs August 5, 2021, comparison (C-ii) shows that the Tac HFST and Baux HFST test sections exhibited the largest friction differential, with both of their May 5, 2025, friction values lower than their initial 2021 baseline values by -16.6%. This differential can probably be attributed to the nature of an HFST. At installation, HFST aggregates are at their most angular and prominent (i.e., macrotexture) and will return very high friction values. The most angular and prominent aggregate particles (e.g., particles nominally embedded in the resin) will invariably be subjected to greater wear and “plucking” relatively quickly, and friction values will decline accordingly but then level off. This phenomenon appears to have been the case with this project’s taconite and bauxite HFST test sections, as shown by their respective histogram trends in Figure 7.31.

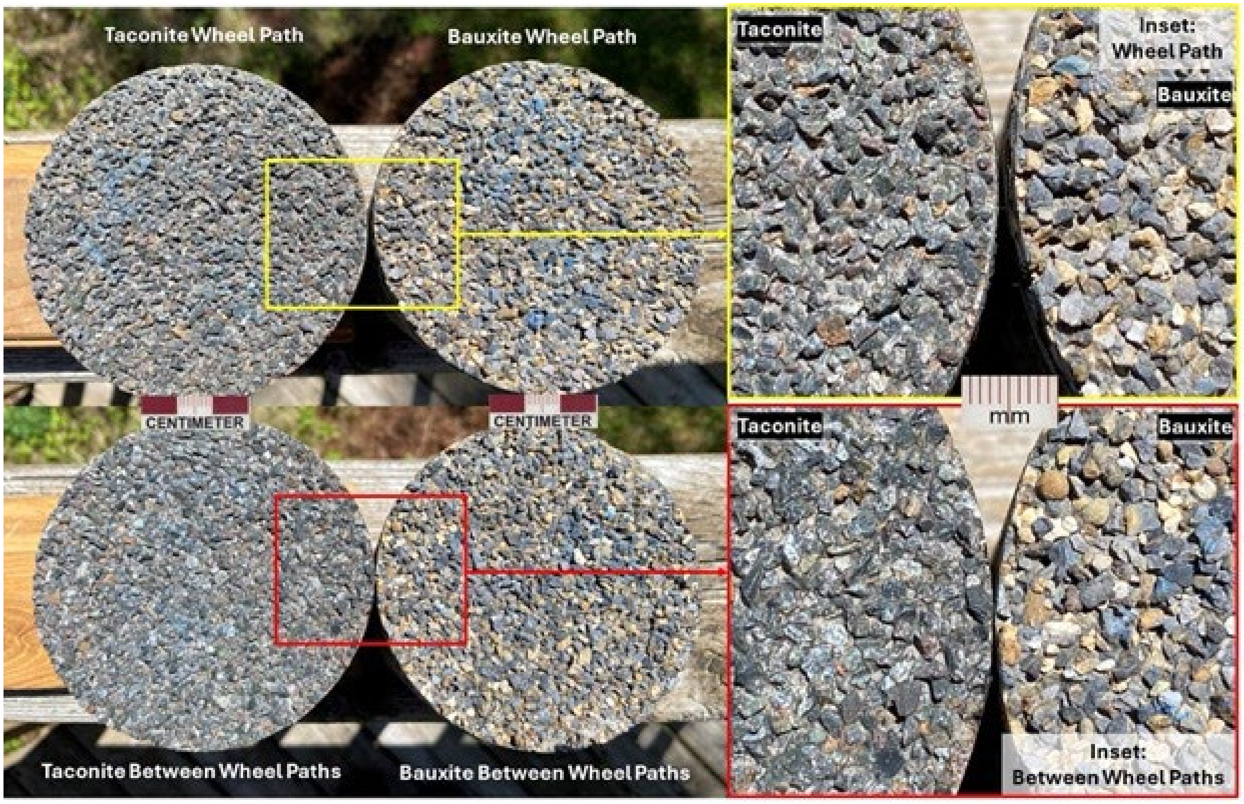
Figure 7.32. Comparison of wheel path and between wheel paths friction values determined by DFT for all tests sections at 40 mph (64.4 km/h) equivalent (chart and data table)



Testing Position	Testing time	Friction Value					
		Control	GSB 8	GSB 6	Tac HFST	Baux HFST	New GSB
Between Wheel Paths	**8/5/2021 & 10/5/2022**	**n/a**	**0.48**	**0.46**	**0.96**	**1.02**	**0.63**
	5/22/2023	0.70	0.69	0.59	0.83	0.88	0.66
	10/2/2023	0.65	0.61	0.57	0.76	0.87	0.67
	4/30/2024	0.64	0.69	0.61	0.83	0.88	0.71
	9/23/2024	0.66	0.53	0.55	0.81	0.90	0.73
	5/5/2025	0.69	0.57	0.56	0.80	0.87	0.69
Wheel Path	**8/5/2021 & 10/5/2022**	**0.61**	**0.48**	**0.46**	**0.96**	**1.02**	**0.63**
	5/22/2023	0.60	0.70	0.56	0.81	0.86	0.68
	10/2/2023	0.55	0.57	0.50	0.78	0.83	0.65
	4/30/2024	0.61	0.68	0.59	0.83	0.89	0.70
	9/23/2024	0.55	0.53	0.40	0.80	0.86	0.62
	5/5/2025	0.60	0.55	0.40	0.80	0.85	0.65
Percent Difference: Wheel Path vs. Between Wheel Paths	**8/5/2021**		0.0%	0.0%	0.0%	0.0%	0.0%
	5/22/2023	-14.5%	1.7%	-5.2%	-2.2%	-2.2%	4.0%
	10/2/2023	-16.0%	-6.0%	-13.1%	2.7%	-4.3%	-2.7%
	4/30/2024	-4.0%	-0.6%	-3.5%	-0.4%	0.8%	-2.2%
	9/23/2024	-15.5%	-0.9%	-26.6%	-0.4%	-4.4%	-15.0%
	5/5/2025	-13.0%	-3.5%	-28.1%	0.7%	-2.7%	-5.6%
	5/5/2025 vs baseline	n/a	14.5%	-12.7%	-16.6%	-16.6%	2.4%

On May 5, 2025, St. Louis County personnel also collected cores from the wheel path and between wheel paths near the project's DFT testing locations at the taconite and bauxite HFST installations (Test Sections 3 and 4) and at the GSB 6 and New GSB installations (Test Sections 2 and 5). The purpose was to visually assess the surface treatments for relative wear. Images of the wheel path and between wheel paths core surfaces are presented in Figure 7.33 and Figure 7.34 for the HFST and GSB treatments, respectively.

Figure 7.33. Photographs of wheel path and between wheel paths core surfaces for the taconite and bauxite HFST treatments; insets on the right are side-by-side closeups of the two aggregate types

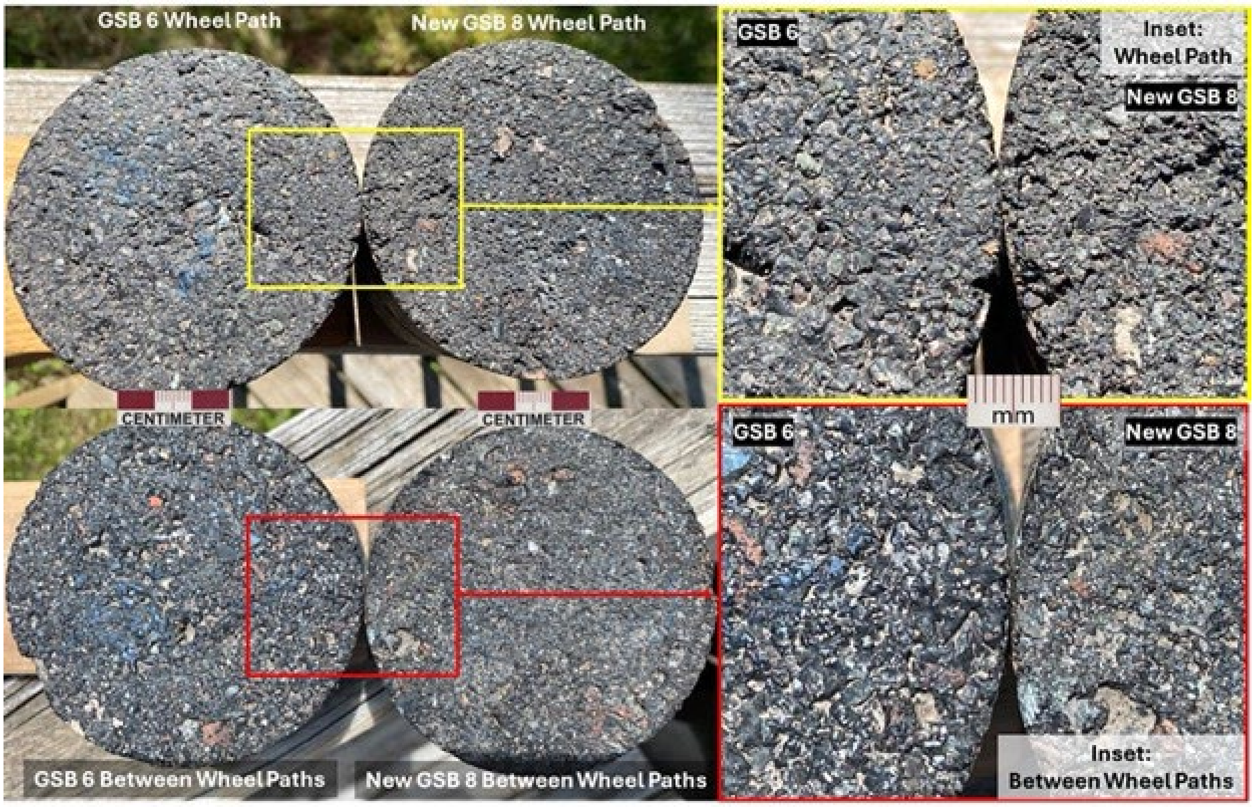


As the magnified insets of Figure 7.33 show, the taconite and bauxite aggregates are well-embedded, and the pavement surfaces have maintained good macrotexture since their 2021 installation. Wheel path and between wheel paths wear differences are difficult to visually discern for these two HFST surface treatments, aside from perhaps a slightly dingier appearance of the wheel path specimens.

The wear differences are more visually apparent for the two GSB pavement preservation surface treatments, especially for the GSB 6 treatment (Figure 7.34). Note the smoother and somewhat “shinier” nature of the GSB 6 surface treatment and the more visible chipseal aggregate showing where the thinner mixture has worn off. As has already been discussed, equipment calibration issues during the 2021 GSB 6 installation (i.e., the aggregate-to-liquid ratio was too low) resulted in friction numbers that were lower than those of the control pavement. And as Figure 7.34C-i shows, GSB 6’s May 5, 2025, wheel path friction numbers were 28.1% lower than its between wheel paths friction numbers.

The test section added in 2022, New GSB 8, was installed with the proper aggregate-to-liquid ratio; it has produced comparable or slightly higher friction numbers than the control since its installation.

Figure 7.34. Photographs of wheel path and between wheel paths core surfaces for the GSB 6 and New GSB 8 surface treatments; insets on the right are side-by-side closeups of the two treatments



The DFT data confirm that the taconite and bauxite HFST Test Sections 3 and 4 (Tac HFST and Baux HFST) have significantly higher friction values – on average by about 40 to 50 percent higher – relative to Control Section 0 (existing chip sealed pavement) and to GSB Sections 1, 2, and 5. Friction values for GSB Section 5 (New GSB -8) are modestly higher than the Control, while those for GSB Section 1 (GSB -8) are slightly lower. GSB Section 2 (GSB -6) has consistently returned lower friction values than the Control, which is attributed to the equipment calibration issue in 2021 (described previously) that resulted in an aggregate application rate that was too low relative to the test section's liquid emulsion application rate.

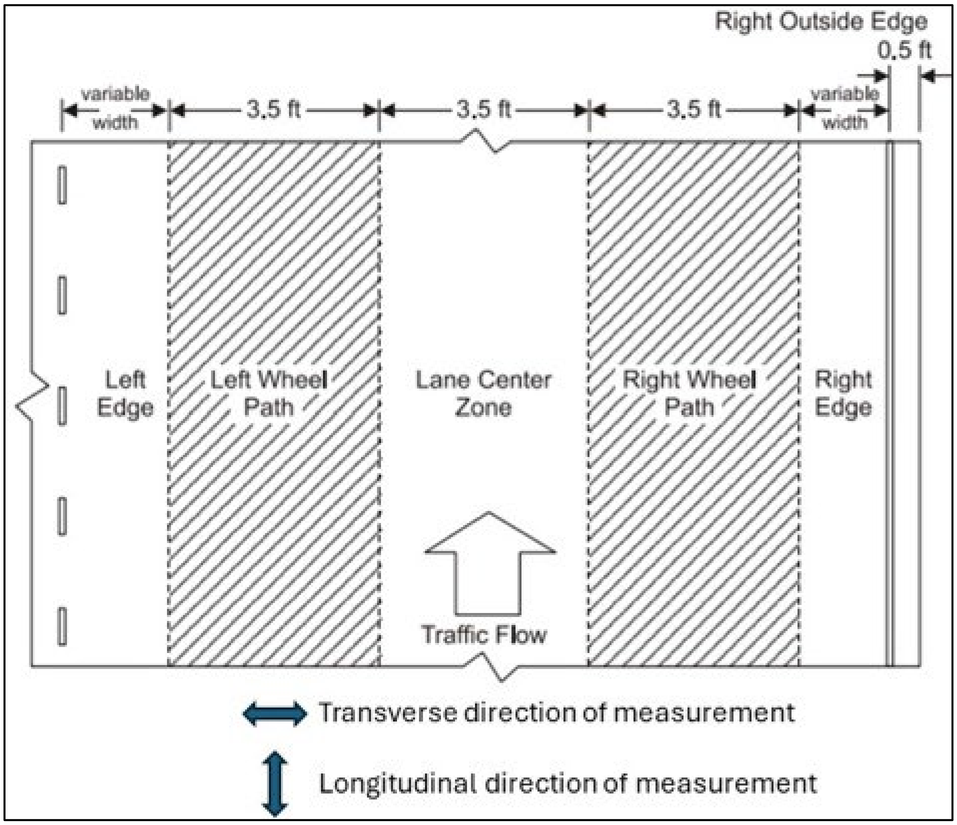
The DFT data also show that both HFST aggregate types are performing comparably, as Taconite HFST Test Section 3's friction numbers have been consistently within six percent of calcined bauxite Test Section 4's friction values (i.e., 0.802 vs 0.848) at a 40 mph (64.4 km/h) speed equivalent, with there being virtually no separation/divergence in their relative friction values since their August 2021 installation.

7.4.2.2 British Pendulum (BP) results through May of 2025

British Pendulum tests were conducted at four locations within each pavement section, typically with four replicates per test. Tests were performed within the right wheel path and between the wheel paths (i.e., in the lane center) of each test section, as shown schematically in Figure 7.35.

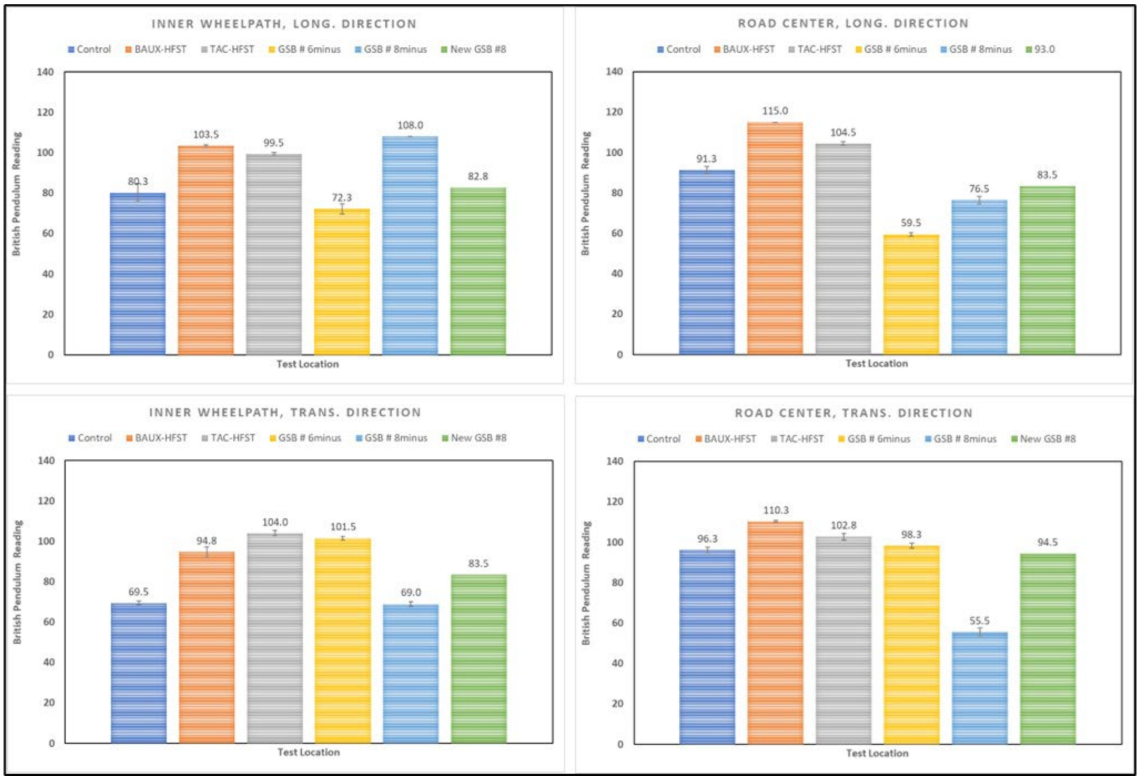
Measurements were made parallel (longitudinal) and perpendicular (transverse) to the direction of traffic to measure the potential influence of vehicle traffic on the orientation of aggregate particles.

Figure 7.35. Illustration of a typical traffic lane showing wheel paths and lane center (between wheel paths) and orientation of BP for conducting transverse and longitudinal measurements. Source: modified from Diefenderfer and Bryant (2006)



The BP data for the five testing dates are presented in Figure 7.36 to Figure 7.41.

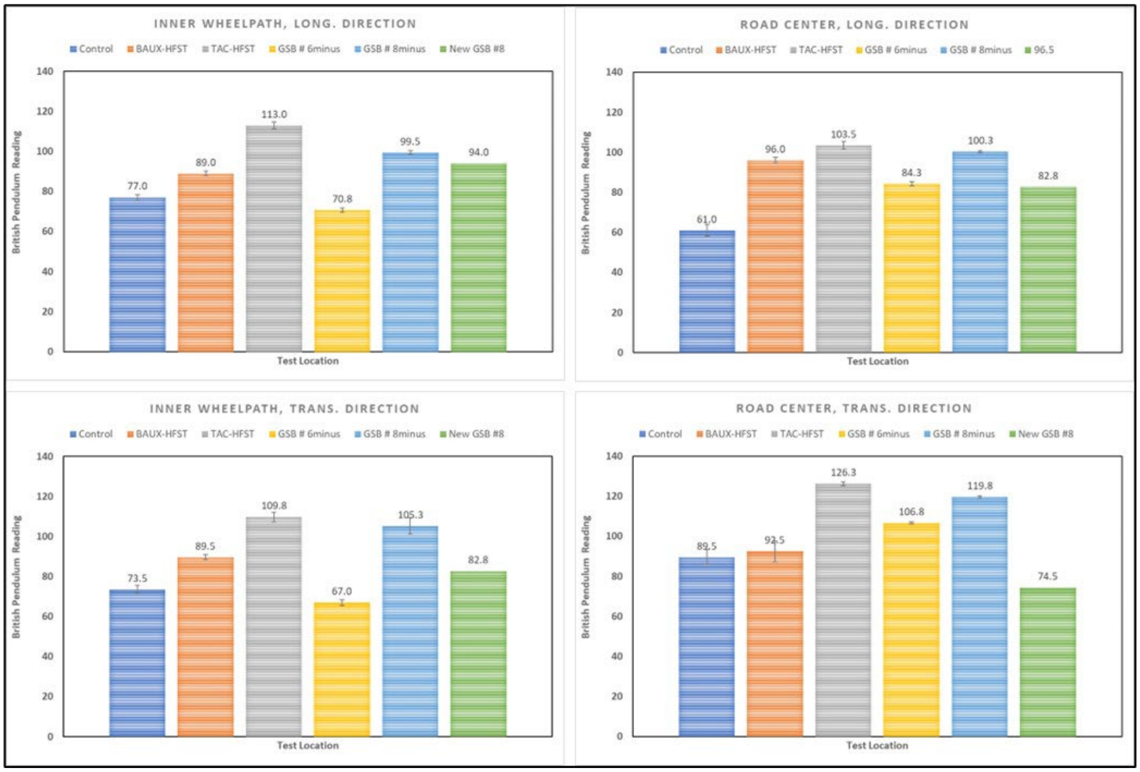
Figure 7.36. British Pendulum test results: October 5, 2022 (charts and data table)



Testing section & Testing time		Friction value			
		Inner wheelpath		Road center	
		Long. Direction	Trans. Direction	Long. Direction	Trans. Direction
Control	1	75	68	94	95
	2	80	70	90	98
	3	80	70	90	96
	4	86	70	91	96
	Ave.	80.3	69.5	91.3	96.3
	Std.dev.	4.5	1.0	1.9	1.3
BAUX-HFST	1	104	91	115	111
	2	104	97	115	110
	3	103	95	115	110
	4	103	96	115	110
	Ave.	103.5	94.8	115.0	110.3
	Std.dev.	0.6	2.6	0.0	0.5
TAC-HFST	1	99	104	104	101
	2	99	102	104	102
	3	100	105	106	103
	4	100	105	104	105
	Ave.	99.5	104.0	104.5	102.8
	Std.dev.	0.6	1.4	1.0	1.7

Testing section & Testing time		Friction value			
		Inner wheelpath		Road center	
		Long. Direction	Trans. Direction	Long. Direction	Trans. Direction
GSB #6min.	1	75	102	60	100
	2	74	102	60	98
	3	70	102	60	98
	4	70	100	58	97
	Ave.	72.3	101.5	59.5	98.3
	Std.dev.	2.6	1.0	1.0	1.3
GSB #8min.	1	108	68	78	55
	2	108	68	78	58
	3	108	70	75	56
	4	108	70	75	53
	Ave.	108.0	69.0	76.5	55.5
	Std.dev.	0.0	1.2	1.7	2.1
New GSB #8	1	81	85	91	95
	2	85	83	95	93
	3	84	83	94	96
	4	81	83	92	94
	Ave.	82.8	83.5	93.0	94.5
	Std.dev.	2.1	1.0	1.8	1.3

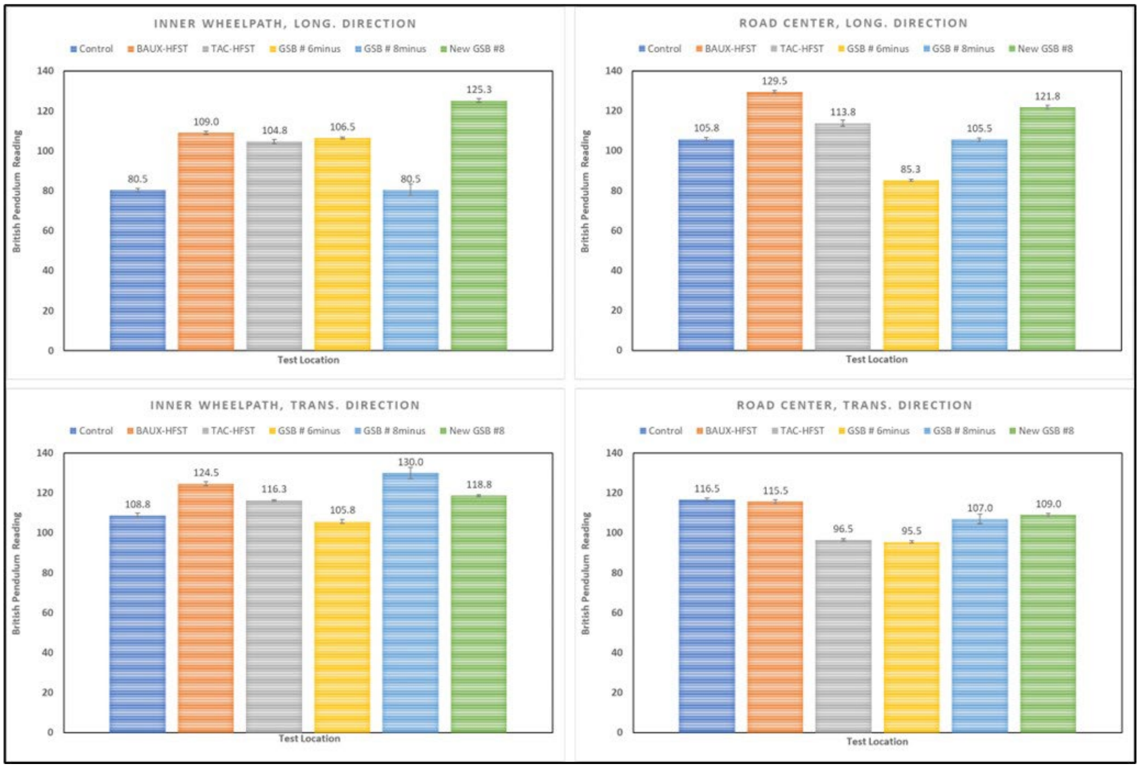
Figure 7.37. British Pendulum test results: May 22, 2023 (charts and data table)



Testing section & Testing time		Friction value			
		Inner wheelpath		Road center	
		Long. Direction	Trans. Direction	Long. Direction	Trans. Direction
Control	1	78	76	60	94
	2	78	74	61	91
	3	75	72	58	88
	4	77	72	65	85
	Ave.	77.0	73.5	61.0	89.5
	Std.dev.	1.4	1.9	2.9	3.9
BAUX-HFST	1	90	90	95	97
	2	90	91	96	95
	3	88	88	98	93
	4	88	89	95	85
	Ave.	89.0	89.5	96.0	92.5
	Std.dev.	1.2	1.3	1.4	5.3
TAC-HFST	1	111	109	103	125
	2	112	110	101	127
	3	114	113	105	126
	4	115	107	105	127
	Ave.	113.0	109.8	103.5	126.3
	Std.dev.	1.8	2.5	1.9	1.0
GSB #6min.	1	70	68	85	107
	2	70	68	84	107
	3	71	67	85	107
	4	72	65	83	106
	Ave.	70.8	67.0	84.3	106.8
	Std.dev.	1.0	1.4	1.0	0.5

Testing section & Testing time		Friction value			
		Inner wheelpath		Road center	
		Long. Direction	Trans. Direction	Long. Direction	Trans. Direction
GSB #8min.	1	100	110	100	120
	2	98	106	101	120
	3	100	105	100	119
	4	100	100	100	120
	Ave.	99.5	105.3	100.3	119.8
	Std.dev.	1.0	4.1	0.5	0.5
New GSB #8	1	96	82	98	75
	2	92	83	96	75
	3	92	83	96	74
	4	96	83	96	74
	Ave.	94.0	82.8	96.5	74.5
	Std.dev.	2.3	0.5	1.0	0.6

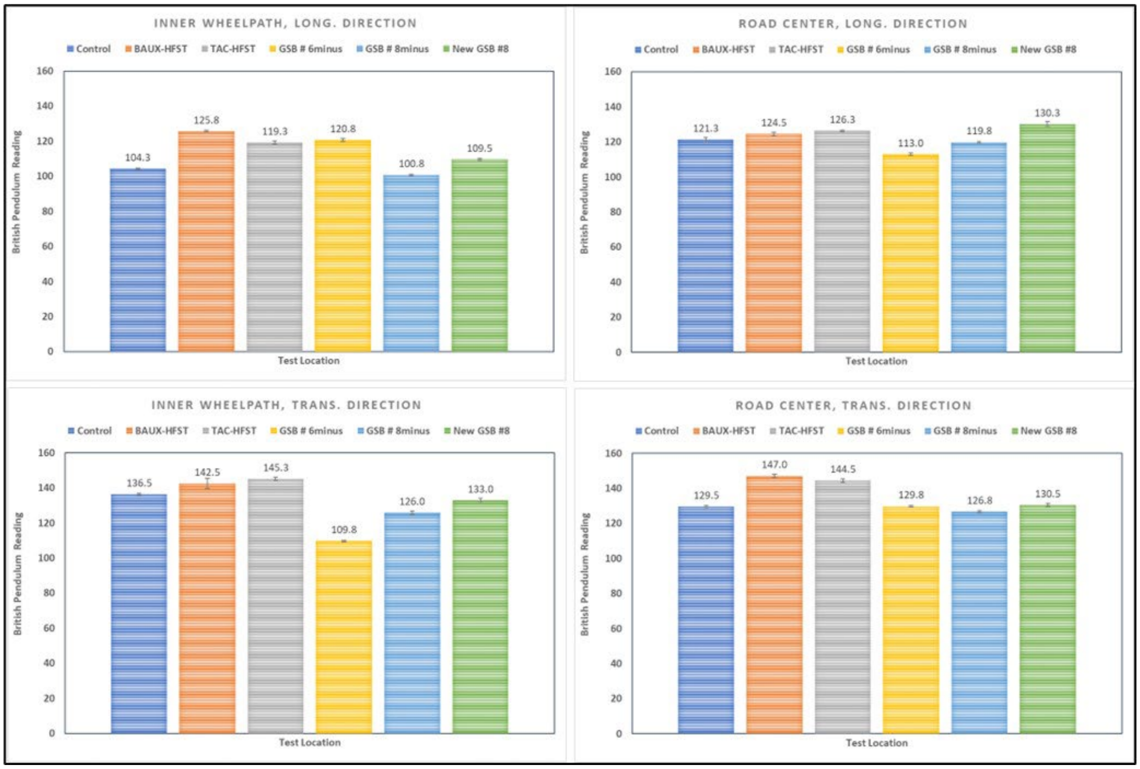
Figure 7.38. British Pendulum test results: October 2, 2023 (charts and data table)



Testing section & Testing time		Friction value			
		Inner wheelpath		Road center	
		Long. Direction	Trans. Direction	Long. Direction	Trans. Direction
Control	1	81	109	107	117
	2	80	109	106	117
	3	81	110	105	115
	4	80	107	105	117
	Ave.	80.5	108.8	105.8	116.5
	Std.dev.	0.6	1.3	1.0	1.0
BAUX-HFST	1	109	125	129	115
	2	109	125	129	115
	3	108	125	130	115
	4	110	123	130	na
	Ave.	109.0	124.5	129.5	115.0
	Std.dev.	0.8	1.0	0.6	0.0
TAC-HFST	1	104	116	113	97
	2	104	116	115	97
	3	105	117	115	96
	4	106	116	112	96
	Ave.	104.8	116.3	113.8	96.5
	Std.dev.	1.0	0.5	1.5	0.6
GSB #6min.	1	107	107	85	95
	2	107	105	85	95
	3	106	105	85	96
	4	106	106	86	96
	Ave.	106.5	105.8	85.3	95.5
	Std.dev.	0.6	1.0	0.5	0.6

Testing section & Testing time		Friction value			
		Inner wheelpath		Road center	
		Long. Direction	Trans. Direction	Long. Direction	Trans. Direction
GSB #8min.	1	83	126	105	104
	2	78	132	105	106
	3	78	132	105	109
	4	83	130	107	109
	Ave.	80.5	130.0	105.5	107.0
	Std.dev.	2.9	2.8	1.0	2.4
New GSB #8	1	125	119	122	110
	2	126	118	121	109
	3	124	119	123	109
	4	126	119	121	108
	Ave.	125.3	118.8	121.8	109.0
	Std.dev.	1.0	0.5	1.0	0.8

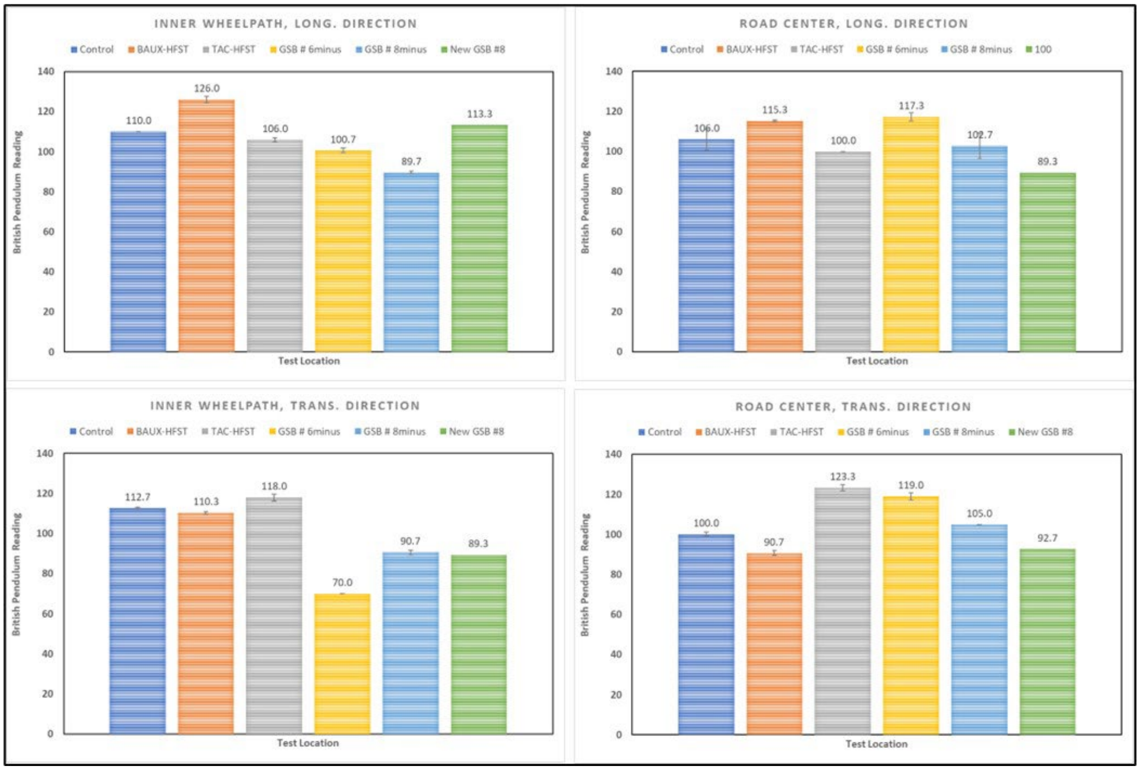
Figure 7.39. British Pendulum test results: April 30, 2024 (charts and data table)



Testing section & Testing time		Friction value			
		Inner wheelpath		Road center	
		Long. Direction	Trans. Direction	Long. Direction	Trans. Direction
Control	1	81	109	107	117
	2	80	109	106	117
	3	81	110	105	115
	4	80	107	105	117
	Ave.	80.5	108.8	105.8	116.5
	Std.dev.	0.6	1.3	1.0	1.0
BAUX-HFST	1	109	125	129	115
	2	109	125	129	115
	3	108	125	130	115
	4	110	123	130	na
	Ave.	109.0	124.5	129.5	115.0
	Std.dev.	0.8	1.0	0.6	0.0
TAC-HFST	1	104	116	113	97
	2	104	116	115	97
	3	105	117	115	96
	4	106	116	112	96
	Ave.	104.8	116.3	113.8	96.5
	Std.dev.	1.0	0.5	1.5	0.6
GSB #6min.	1	107	107	85	95
	2	107	105	85	95
	3	106	105	85	96
	4	106	106	86	96
	Ave.	106.5	105.8	85.3	95.5
	Std.dev.	0.6	1.0	0.5	0.6

Testing section & Testing time		Friction value			
		Inner wheelpath		Road center	
		Long. Direction	Trans. Direction	Long. Direction	Trans. Direction
GSB #8min.	1	83	126	105	104
	2	78	132	105	106
	3	78	132	105	109
	4	83	130	107	109
	Ave.	80.5	130.0	105.5	107.0
	Std.dev.	2.9	2.8	1.0	2.4
New GSB #8	1	125	119	122	110
	2	126	118	121	109
	3	124	119	123	109
	4	126	119	121	108
	Ave.	125.3	118.8	121.8	109.0
	Std.dev.	1.0	0.5	1.0	0.8

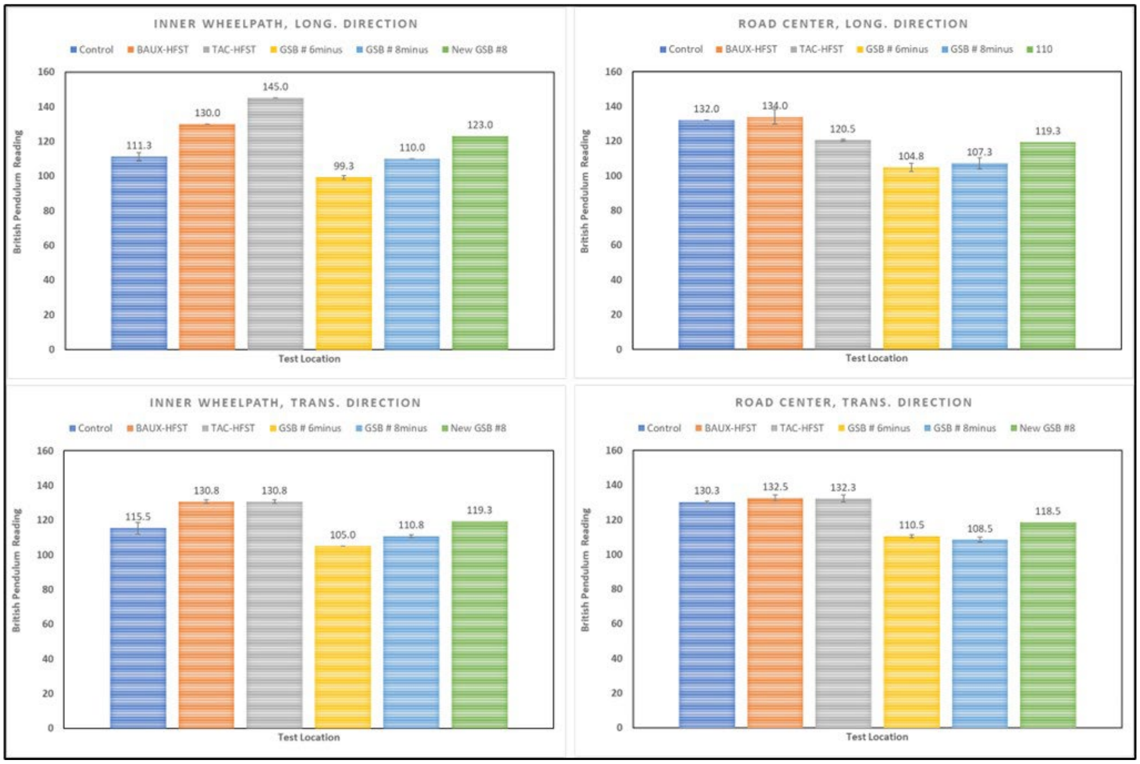
Figure 7.40. British Pendulum test results: September 23, 2024 (charts and data table)



Testing section & Testing time		Friction value			
		Inner wheelpath		Road center	
		Long. Direction	Trans. Direction	Long. Direction	Trans. Direction
Control	1	110	113	110	101
	2	110	113	108	100
	3	110	112	100	99
	Ave.	110.0	112.7	106.0	100.0
	Std.dev.	0.0	0.6	5.3	1.0
BAUX-HFST	1	125	110	116	92
	2	125	110	115	90
	3	128	111	115	90
	Ave.	126.0	110.3	115.3	90.7
	Std.dev.	1.7	0.6	0.6	1.2
TAC-HFST	1	107	120	100	123
	2	106	117	100	125
	3	105	117	100	122
	Ave.	106.0	118.0	100.0	123.3
	Std.dev.	1.0	1.7	0.0	1.5
GSB #6min.	1	102	70	115	117
	2	100	70	119	120
	3	100	70	118	120
	Ave.	100.7	70.0	117.3	119.0
	Std.dev.	1.2	0.0	2.1	1.7

Testing section & Testing time		Friction value			
		Inner wheelpath		Road center	
		Long. Direction	Trans. Direction	Long. Direction	Trans. Direction
GSB #8min.	1	90	90	110	105
	2	89	90	100	105
	3	90	92	98	105
	Ave.	89.7	90.7	102.7	105.0
	Std.dev.	0.6	1.2	6.4	0.0
New GSB #8	1	110	90	100	93
	2	115	88	100	93
	3	115	90	100	92
	Ave.	113.3	89.3	100.0	92.7
	Std.dev.	2.9	1.2	0.0	0.6

Figure 7.41. British Pendulum test results: May 5, 2025 (charts and data table)



Testing section & Testing time		Friction value			
		Inner wheelpath		Road center	
		Long. Direction	Trans. Direction	Long. Direction	Trans. Direction
Control	1	110	120	132	130
	2	110	115	132	130
	3	115	115	132	130
	4	110	112	132	131
	Ave.	111.3	115.5	132.0	130.3
	Std.dev.	2.5	3.3	0.0	0.5
BAUX-HFST	1	130	132	140	135
	2	130	130	133	132
	3	130	131	133	132
	4	130	130	130	131
	Ave.	130.0	130.8	134.0	132.5
	Std.dev.	0.0	1.0	4.2	1.7
TAC-HFST	1	145	132	120	135
	2	145	130	120	131
	3	145	130	121	131
	4	145	131	121	132
	Ave.	145.0	130.8	120.5	132.3
	Std.dev.	0.0	1.0	0.6	1.9
GSB #6min.	1	100	105	108	112
	2	100	105	105	110
	3	99	105	103	110
	4	98	105	103	110
	Ave.	99.3	105.0	104.8	110.5
	Std.dev.	1.0	0.0	2.4	1.0

Testing section & Testing time		Friction value			
		Inner wheelpath		Road center	
		Long. Direction	Trans. Direction	Long. Direction	Trans. Direction
GSB #8min.	1	110	112	106	110
	2	110	111	105	109
	3	110	110	106	107
	4	110	110	112	108
	Ave.	110.0	110.8	107.3	108.5
	Std.dev.	0.0	1.0	3.2	1.3
New GSB #8	1	128	120	110	120
	2	122	119	110	118
	3	121	119	110	118
	4	121	119	110	118
	Ave.	123.0	119.3	110.0	118.5
	Std.dev.	3.4	0.5	0.0	1.0

Table 7.2 summarizes the project's BP data in its entirety. Averages for each measurement are shown.

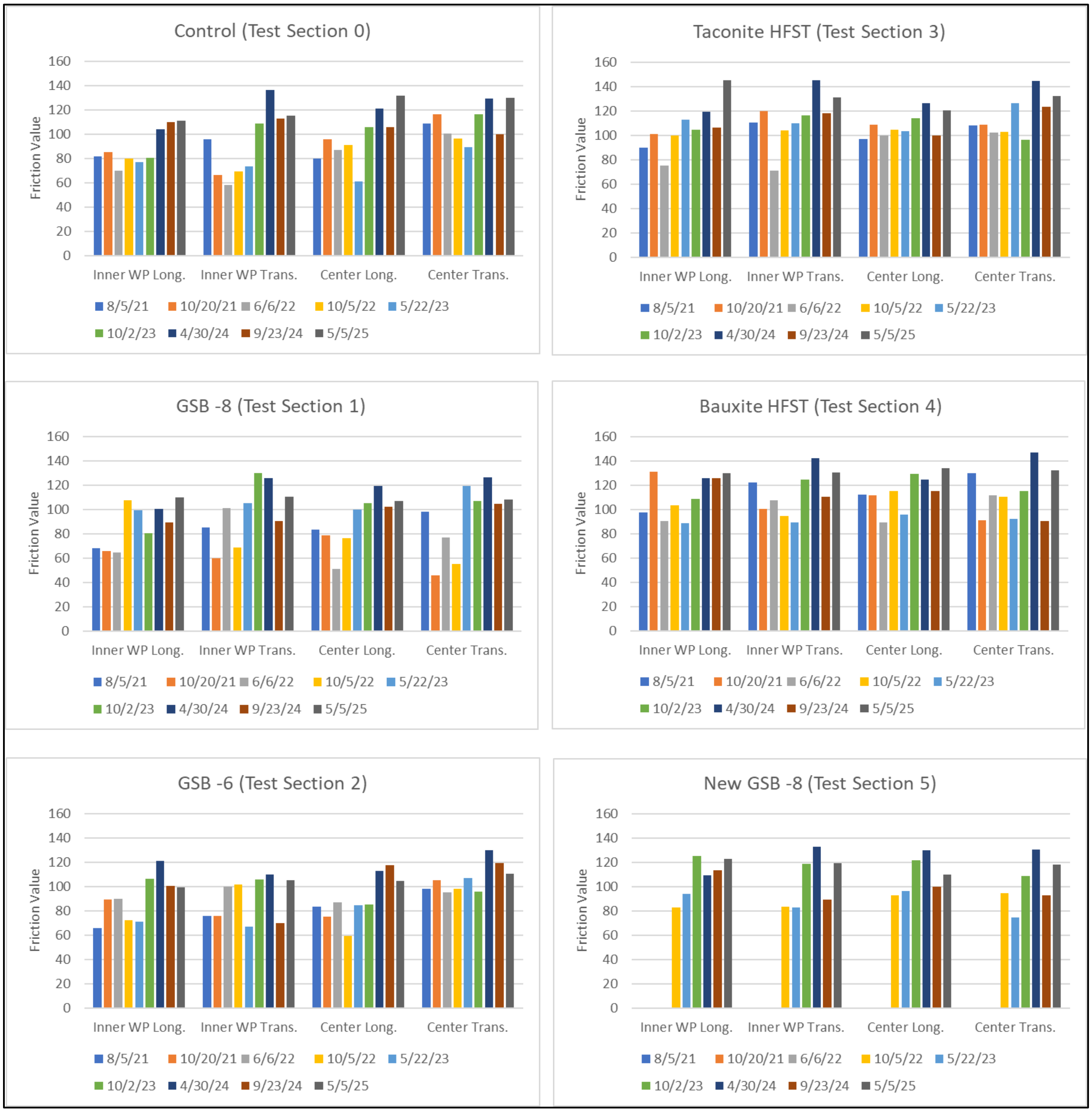
Table 7.2. British Pendulum results for entire project.

Test Date	Test Section	Inner Wheel Path: Longitudinal	Inner Wheel Path: Transverse	Wheel Path Average	Between Wheel Paths: Longitudinal	Between Wheel Paths: Transverse	Between Wheel Paths Average	Longitudinal Average	Transverse Average	Composite Average
8/5/2021	**Control**	81.8	96.0	88.9	80.0	108.8	94.4	80.9	102.4	91.6
10/20/2021	**Control**	85.0	66.3	75.6	96.0	116.3	106.1	90.5	91.3	90.9
6/6/2022	**Control**	70.0	58.5	64.3	87.0	100.8	93.9	78.5	79.6	79.1
10/5/2022	**Control**	80.3	69.5	74.9	91.3	96.3	93.8	85.8	82.9	84.3
5/22/2023	**Control**	77.0	73.5	75.3	61.0	89.5	75.3	69.0	81.5	75.3
10/2/2023	**Control**	80.5	108.8	94.6	105.8	116.5	111.1	93.1	112.6	102.9
4/30/2024	**Control**	104.3	136.5	120.4	121.3	129.5	125.4	112.8	133.0	122.9
9/23/2024	**Control**	110.0	112.7	111.3	106.0	100.0	103.0	108.0	106.3	107.2
5/5/2025	**Control**	111.3	115.5	113.4	132.0	130.3	131.1	121.6	122.9	122.3
8/5/2021	**GSB 8**	68.5	85.5	77.0	83.5	98.3	90.9	76.0	91.9	83.9
10/20/2021	**GSB 8**	65.8	60.0	62.9	78.8	46.3	62.5	72.3	53.1	62.7
6/6/2022	**GSB 8**	64.8	101.3	83.0	51.5	77.3	64.4	58.1	89.3	73.7
10/5/2022	**GSB 8**	108.0	69.0	88.5	76.5	55.5	66.0	92.3	62.3	77.3
5/22/2023	**GSB 8**	99.5	105.3	102.4	100.3	119.8	110.0	99.9	112.5	106.2
10/2/2023	**GSB 8**	80.5	130.0	105.3	105.5	107.0	106.3	93.0	118.5	105.8
4/30/2024	**GSB 8**	100.8	126.0	113.4	119.8	126.8	123.3	110.3	126.4	118.3
9/23/2024	**GSB 8**	89.7	90.7	90.2	102.7	105.0	103.8	96.2	97.8	97.0
5/5/2025	**GSB 8**	110.0	110.8	110.4	107.3	108.5	107.9	108.6	109.6	109.1
8/5/2021	**GSB 6**	65.8	76.0	70.9	83.5	98.3	90.9	74.6	87.1	80.9
10/20/2021	**GSB 6**	89.5	75.5	82.5	75.3	105.0	90.1	82.4	90.3	86.3
6/6/2022	**GSB 6**	90.0	100.0	95.0	87.0	95.3	91.1	88.5	97.6	93.1
10/5/2022	**GSB 6**	72.3	101.5	86.9	59.5	98.3	78.9	65.9	99.9	82.9
5/22/2023	**GSB 6**	70.8	67.0	68.9	84.3	106.8	95.5	77.5	86.9	82.2
10/2/2023	**GSB 6**	106.5	105.8	106.1	85.3	95.5	90.4	95.9	100.6	98.3
4/30/2024	**GSB 6**	120.8	109.8	115.3	113.0	129.8	121.4	116.9	119.8	118.3
9/23/2024	**GSB 6**	100.7	70.0	85.3	117.3	119.0	118.2	109.0	94.5	101.8
5/5/2025	**GSB 6**	99.3	105.0	102.1	104.8	110.5	107.6	102.0	107.8	104.9
8/5/2021	**Tac HFST**	89.8	110.3	100.0	97.0	108.0	102.5	93.4	109.1	101.3
10/20/2021	**Tac HFST**	101.0	120.0	110.5	108.8	108.8	108.8	104.9	114.4	109.6
6/6/2022	**Tac HFST**	75.3	70.8	73.0	100.0	102.3	101.1	87.6	86.5	87.1
10/5/2022	**Tac HFST**	99.5	104.0	101.8	104.5	102.8	103.6	102.0	103.4	102.7
5/22/2023	**Tac HFST**	113.0	109.8	111.4	103.5	126.3	114.9	108.3	118.0	113.1
10/2/2023	**Tac HFST**	104.8	116.3	110.5	113.8	96.5	105.1	109.3	106.4	107.8
4/30/2024	**Tac HFST**	119.3	145.3	132.3	126.3	144.5	135.4	122.8	144.9	133.8
9/23/2024	**Tac HFST**	106.0	118.0	112.0	100.0	123.3	111.7	103.0	120.7	111.8
5/5/2025	**Tac HFST**	145.0	130.8	137.9	120.5	132.3	126.4	132.8	131.5	132.1
8/5/2021	**Baux HFST**	97.3	122.5	109.9	112.0	130.0	121.0	104.6	126.3	115.4
10/20/2021	**Baux HFST**	131.3	100.5	115.9	111.8	91.3	101.5	121.5	95.9	108.7
6/6/2022	**Baux HFST**	90.8	107.5	99.1	89.5	111.8	100.6	90.1	109.6	99.9
10/5/2022	**Baux HFST**	103.5	94.8	99.1	115.0	110.3	112.6	109.3	102.5	105.9
5/22/2023	**Baux HFST**	89.0	89.5	89.3	96.0	92.5	94.3	92.5	91.0	91.8
10/2/2023	**Baux HFST**	109.0	124.5	116.8	129.5	115.0	122.3	119.3	119.8	119.5
4/30/2024	**Baux HFST**	125.8	142.5	134.1	124.5	147.0	135.8	125.1	144.8	134.9
9/23/2024	**Baux HFST**	126.0	110.3	118.2	115.3	90.7	103.0	120.7	100.5	110.6
5/5/2025	**Baux HFST**	130.0	130.8	130.4	134.0	132.5	133.3	132.0	131.6	131.8
8/5/2021	**New GSB**									
10/20/2021	**New GSB**									
6/6/2022	**New GSB**									

Test Date	Test Section	Inner Wheel Path: Longitudinal	Inner Wheel Path: Transverse	Wheel Path Average	Between Wheel Paths: Longitudinal	Between Wheel Paths: Transverse	Between Wheel Paths Average	Longitudinal Average	Transverse Average	Composite Average
10/5/2022	**New GSB**	82.8	83.5	83.1	93.0	94.5	93.8	87.9	89.0	88.4
5/22/2023	**New GSB**	94.0	82.8	88.4	96.5	74.5	85.5	95.3	78.6	86.9
10/2/2023	**New GSB**	125.3	118.8	122.0	121.8	109.0	115.4	123.5	113.9	118.7
4/30/2024	**New GSB**	109.5	133.0	121.3	130.3	130.5	130.4	119.9	131.8	125.8
9/23/2024	**New GSB**	113.3	89.3	101.3	100.0	92.7	96.3	106.7	91.0	98.8
5/5/2025	**New GSB**	123.0	119.3	121.1	110.0	118.5	114.3	116.5	118.9	117.7

The BP data exhibit greater variability than the DFT data from test period to test period, and even from pavement treatment to pavement treatment, as illustrated in Figure 7.42.

Figure 7.42. Histogram plots of British Pendulum results for entire project, by test section



This variability may be due, in part, to the nature of the British Pendulum test itself, since its readings represent testing of a small footprint spot of pavement at a single testing speed of ~10 km/h (~6 mph) (i.e., the speed of the pendulum at the bottom of its swing as its rubber slider contacts the pavement surface). By comparison, the DFT has a significantly larger circular testing footprint and records friction values over a range of speeds (0 to 80 km/h, or 0 to 50 mph) during a single test. Note also the friction values recorded by the BP for the 10/2/23, 4/30/24, 9/23/24, and 5/5/25 test dates are generally elevated relative to the first five tests conducted from 8/21/21 through 5/22/23. When composited average BP friction values for all nine test dates are plotted against those of the DFT, the correlation is modest (Fig. 7.43A). But when tests performed from 8/21/21 through 5/22/23 and the tests performed from 10/2/23 through 5/5/25 are compared separately to the DFT's for the same testing dates, they form two discernible populations that are more clearly correlated (Fig. 7.43B). This separate but parallel grouping suggests that the four most recent tests may be reflecting a change affecting the BP instrument's measurement of friction, such as a new rubber slider, rather than a significant change (increase) in the friction characteristics of the tested pavements. If the pavement's friction characteristics had indeed increased, then the DFT's numbers should also have reflected that change to the same degree as the BP's, but they did not.

7.4.2.3 Locked Wheel Pavement Friction Tester (LWPFT) results through Spring of 2025

To recap, the LWPFT has been deployed up to two times per year and operated at a target testing speed of 40 mph (64.4 km/h). The LWPFT made five replicate runs at the project site on August 17, 2021, to establish baseline values for each test section, including the existing chip sealed pavement (Control). Thereafter, the LWPFT made three replicate runs over each pavement section. Results (replicate run averages) for all six LWPFT tests performed during the project through May 28, 2025, are summarized in Figure 7.44.

Similar to DFT results, the LWPFT showed that the taconite and bauxite HFST test sections clearly have the highest skid numbers/friction numbers, and that both aggregate types are performing comparably. No departure/divergence in friction values since their August 2021 installation were observed, as Figure 7.45A and A' illustrate. The GSB test section data illustrated in Figure 7.45B and B' shows that the GSB 8 skid/friction numbers are comparable to the chipseal Control (Section 0), and that the New GSB 8 test section's skid/friction numbers are slightly higher than the Control. GSB 6 (Section 2) skid/friction numbers remain lower than the Control.

Figure 7.43. Scatter plots of BP and DFT measurements: A=all tests; B=all tests showing two populations

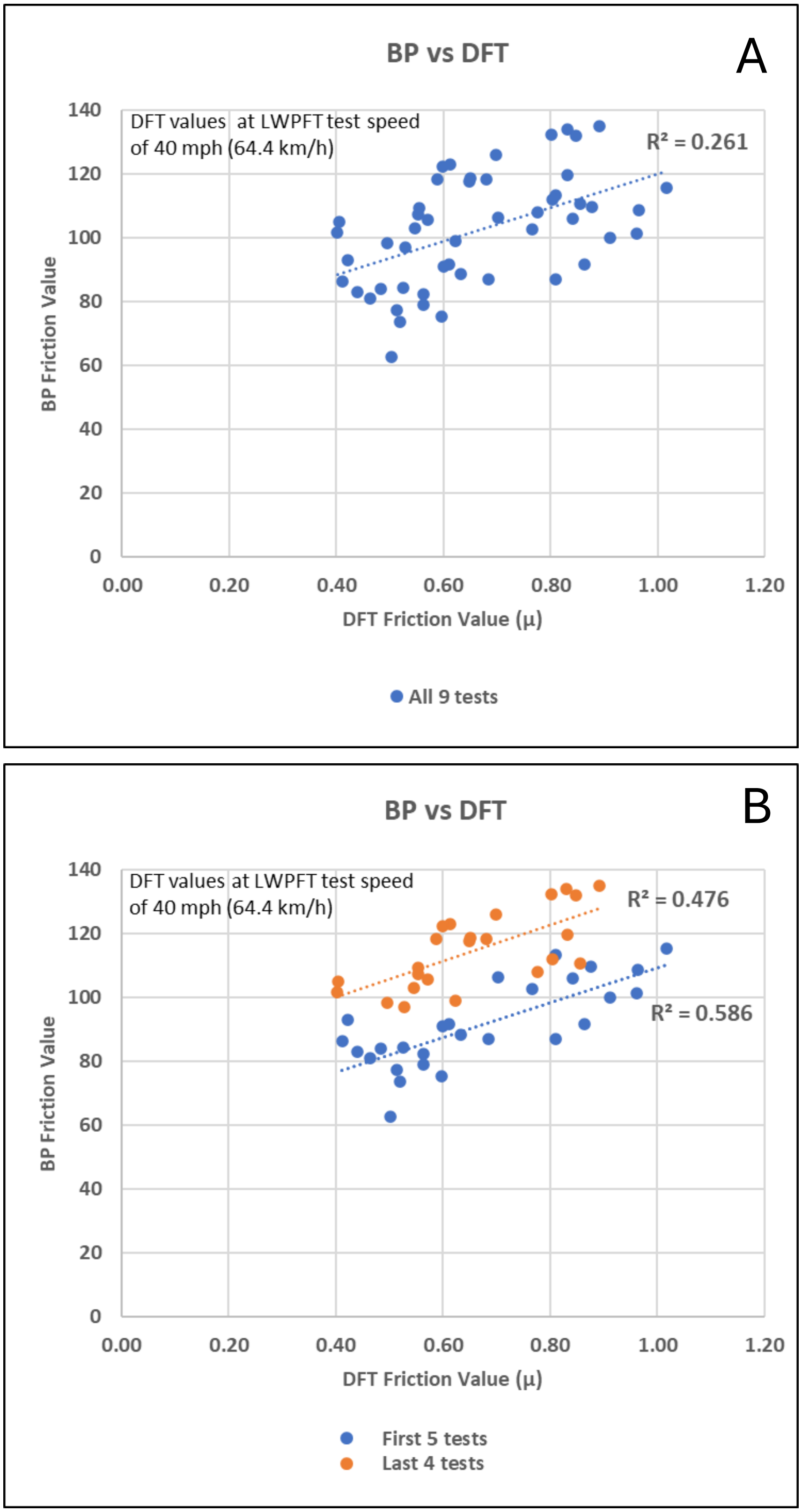


Figure 7.44. Locked Wheel Pavement Friction Tester results through May 28, 2025: average of replicate runs

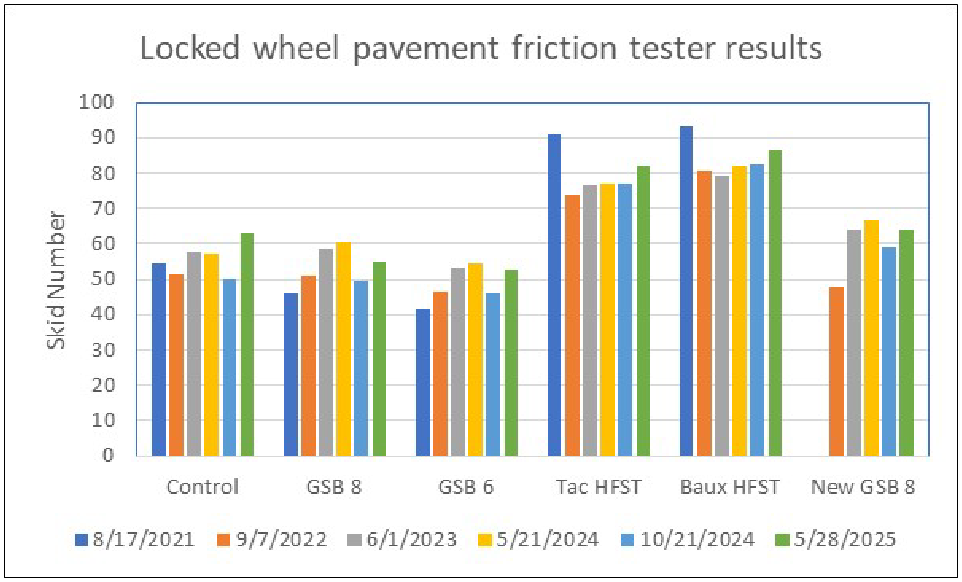
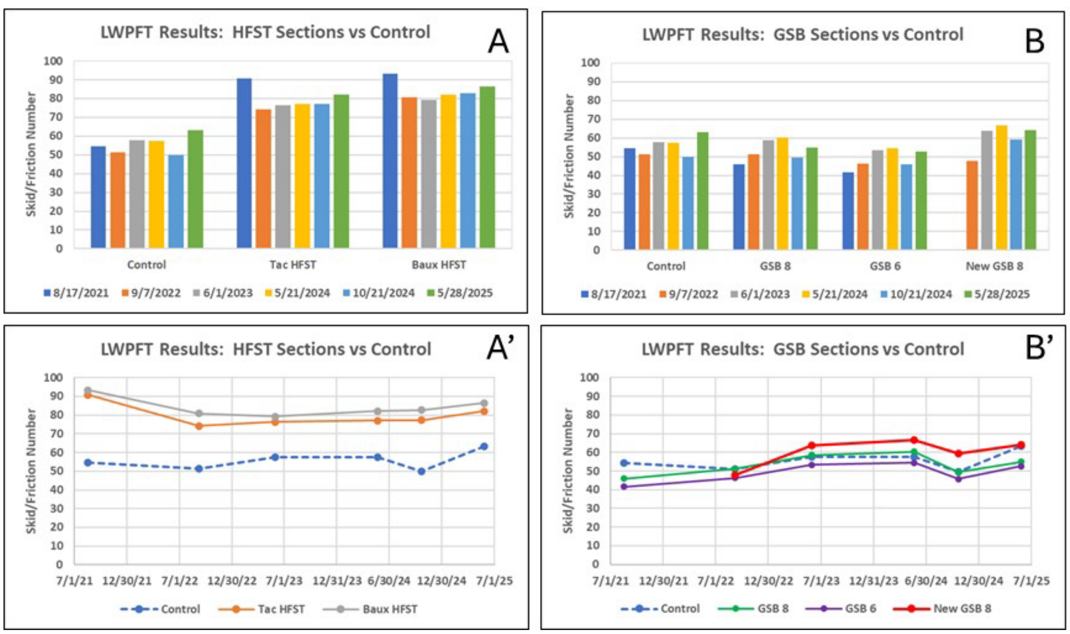
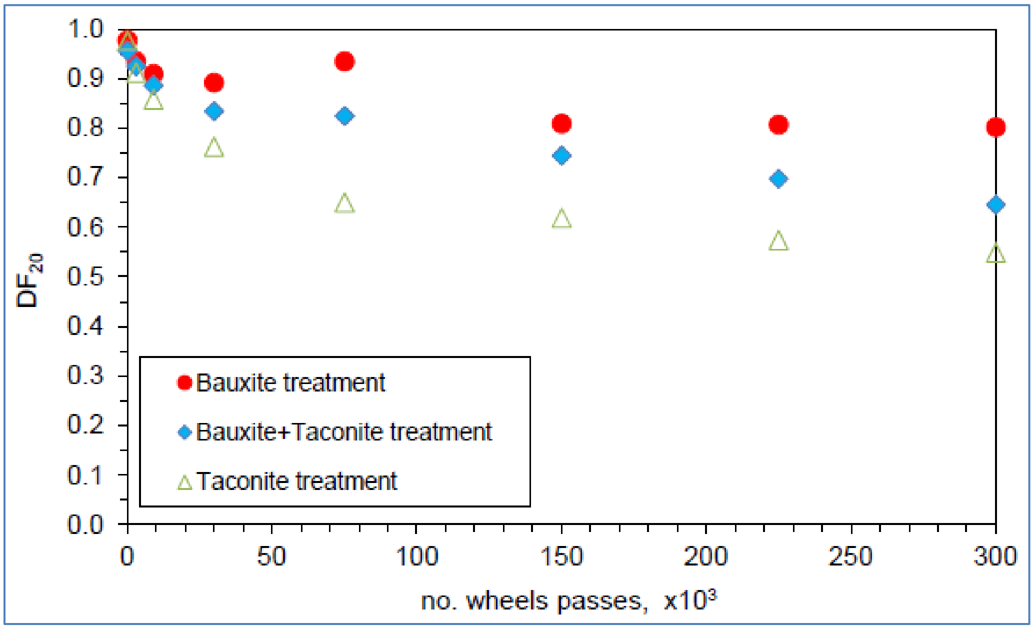


Figure 7.45. LWPFT results for HFST sections (A and A') and GSB sections (B and B') relative to the control pavement



The DFT and LWPFT findings illustrated in Figure 7.43, Figure 7.44 (DFT) and Figure 7.45 (LWPFT) differ significantly from the lab-based results produced by the North Central Superpave Center's 2021 testing of the specimen slabs using the Circular Track Polishing Machine (CTPM), as described in Chapter 4. The CTPM simulated the effects of traffic moving over a surface by subjecting the test specimens to the equivalent of 300K wheel-passes. Figure 7.46 shows the NCSC's dynamic friction tester reading at 20 km/h (DFT_{20}), versus wheel passes of the polishing machine. A larger separation between the two aggregates' friction values was shown as testing progressed. The 100% bauxite-treated specimen slabs had the highest friction values throughout, followed by the 50:50 bauxite-taconite blend and 100% taconite specimens.

Figure 7.46. DFT_{20} vs. wheel passes (Source: Shah, 2021)



The NCSC's laboratory test findings reflect the hardness differential between the two aggregate types. However, the magnitude of the difference in friction between the 100% bauxite and 100% taconite treated specimens, as determined by NCSC's testing, is significantly greater than what was observed in this project's field testing through May of 2025, representing a conservative estimate of 2 *million* post-installation wheel-passes by actual vehicle traffic. The estimate is based on CSAH 15's 2023 average annual daily traffic (AADT) of 923, a number taken from MnDOT's Traffic Mapping Application: https://www.dot.state.mn.us/traffic/data/tma.html.

This project's pavement treatment test sections were also subjected to four seasons of snowplowing.

This can be explained by the fact that the Circular Track Polishing Machine method used by NCSC (and others) imparts a degree of wear that is more extreme than what a pavement surface would experience under typical traffic conditions. For example, the method's small radius produces an action that is more akin to a tire constantly turning sharply on a pavement's surface rather than traveling along a linear or gently curving path. Under such laboratory testing conditions, the hardest aggregate (calcined bauxite) will invariably prevail.

This is why the project's emphasis on direct field testing of the two aggregate materials was so important, because nothing captures better the performance of pavement treatments subjected to actual traffic and environmental conditions than direct field testing does. Consequently, the quantitative results produced by more than four years of field testing (through the spring of 2025) showed that the taconite friction aggregate product used on this project can provide comparable friction performance to calcined bauxite in similar HFST-type applications on low-volume roads.

Further field testing is recommended, especially on horizontal curves where HFST is most often applied, where tangential forces are greatest, and over a range of AADTs.

7.4.2.4 SCRIM testing results (July 26, 2024)

The project team coordinated with WDM USA (hereafter referred to as WDM) to test its Sideway-force Coefficient Routine Investigation Machine (SCRIM) at the CSAH 15 Munger Shaw Road site on July 26, 2024. "Retros" (reflectors) were placed by WDM personnel at the beginning and end of each pavement section, which the SCRIM's on-board sensor detected for geospatially pinpointing its position. To simulate a wet pavement, a calibrated flow of water was delivered by a nozzle ahead of the SCRIM's sideway force measurement wheel (Figure 7.47).

Figure 7.47. SCRIM sideway force measurement wheel and water delivery nozzle

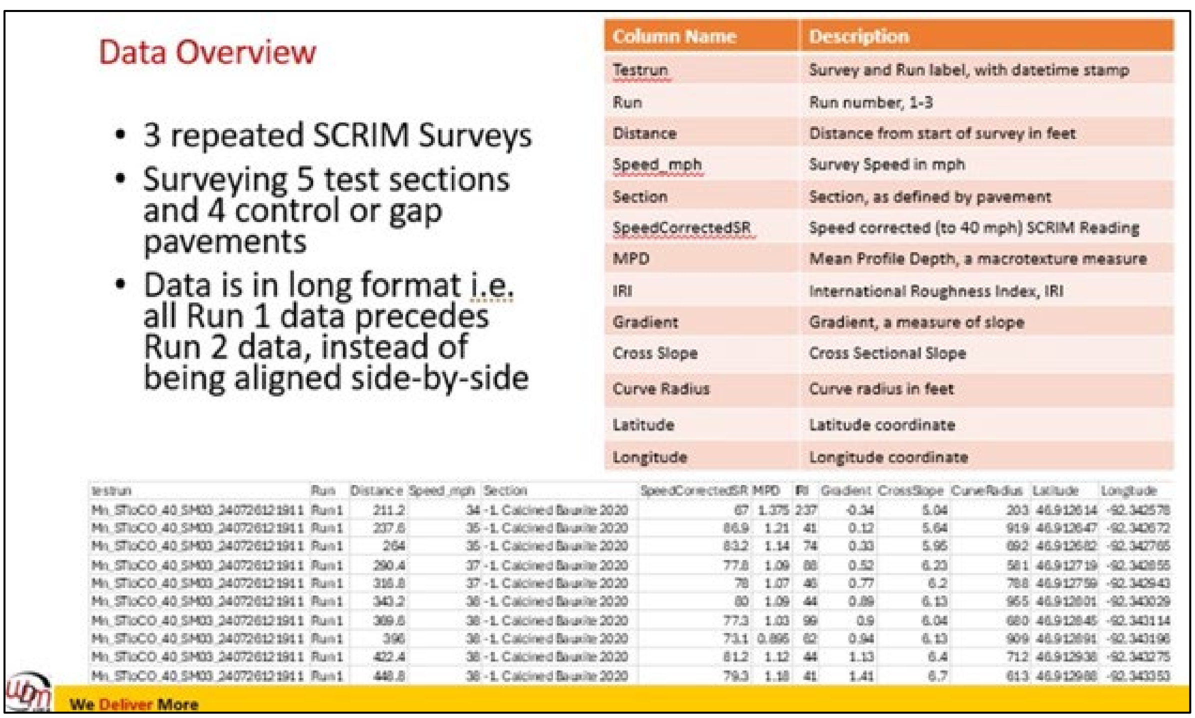
As described by WDM Vice President Ryland Potter (personal communication, July 29, 2024), "The theoretical water film thickness is 0.5mm (which assumes the pavement surface is perfectly dense, smooth, and horizontal), so the flow rate is adjusted based on the speed of the vehicle to achieve the theoretical value. The actual water film thickness under the wheel will depend on the porosity, texture, and gradient of the pavement."

Figure 7.48 shows the SCRIM in operation at the project test site. Note the water being applied to the pavement surface.

Figure 7.48. SCRIM in operation at the project test site on July 26, 2024

On September 5, 2024, WDM provided the investigators with an Excel spreadsheet and a PowerPoint summary of the July 26, 2024, SCRIM test. The PowerPoint summary also explains how WDM performed its testing, the spreadsheet's data content, and how it generated friction and macrotexture results. With WDM's approval, extracts of the PowerPoint summary are included below, while the entire PowerPoint slide deck, titled, "*St. Louis County, CSAH 15, Munger Shaw Road SCRIM Data Review"*, is provided in Appendix F. WDM's Data Overview slide is presented in Figure 7.49.

Figure 7.49. SCRIM data overview slide for July 26, 2024, testing (Source: WDM)



The SCRIM conducted three runs (surveys) – corrected to 40 mph (64.4 km/h) – which matches the LWPFT's standard testing speed.

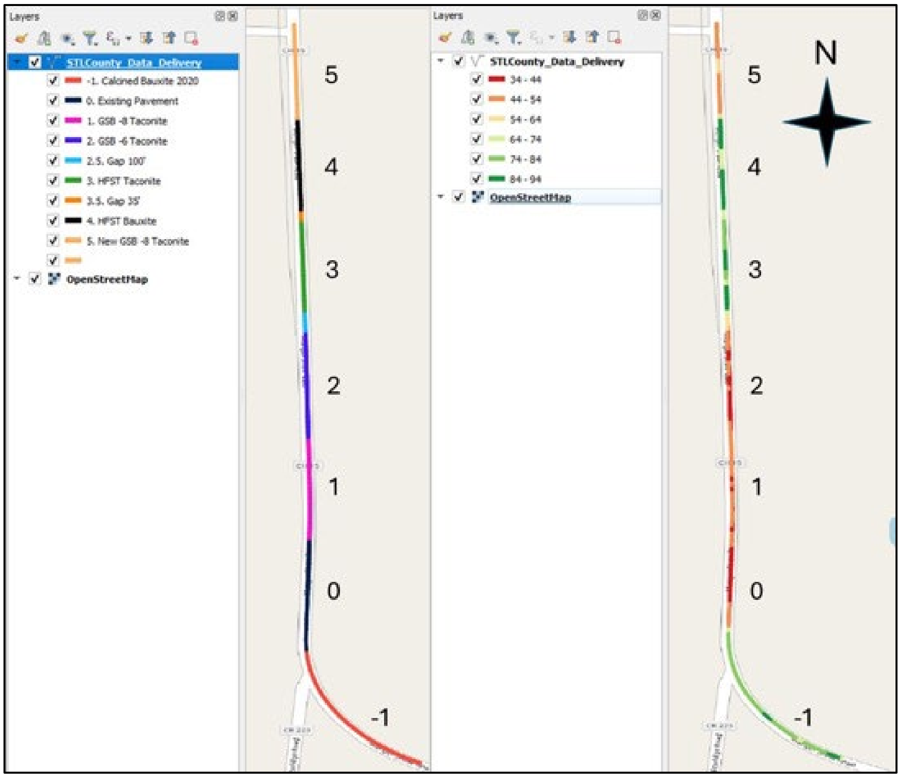
WDM uses friction measurement criteria based on the measured friction (SR) corrected to 40 mph:

- Range: 10 – 120
- Poor Friction: < 45
- Investigatory Level/Minimum Sufficient Friction: >56
- Great Friction: > 67
- HFST Friction Range: 75 – 105

The SCRIM test included a horizontal curve (#015D) immediately to the south of the project's test sections (refer to Figure 7.2) that received a calcined bauxite HFST treatment in 2020, providing the project with an additional HFST data point for comparison. The horizontal curve was one of several commissioned by St. Louis County for HFST treatment in 2020.

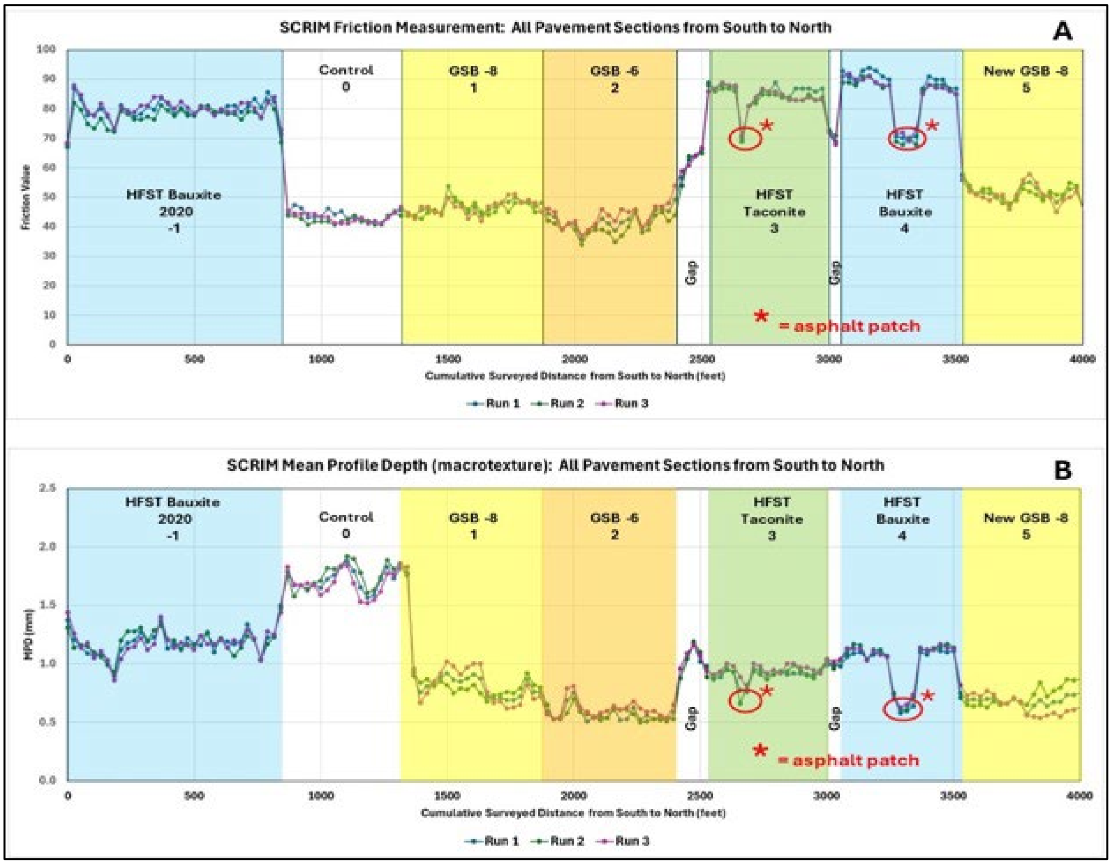
Figure 7.50, extracted from WDM's slide deck, shows the geospatially referenced path of the SCRIM's triplicate surveys, the sections of pavement it tested, and a color-coded representation of each section's friction numbers. Note the green shaded intervals on the right side of Figure 7.50 have the highest friction numbers; they coincide with the HFST sections (-1, 3, and 4) and fall within the HFST Friction Range.

Figure 7.50. Geospatially referenced path and color-coded friction values of the SCRIM's project test site survey (Source: WDM)



The SCRIM recorded friction and mean profile depth (MPD; i.e., macrotexture) data every 8 meters (26.3 feet). This level of data-recording detail not only discerned transitions from one pavement treatment test section to another and where non-treated gaps between test sections were located, it also identified pavement surface anomalies. For example, asphalt patches were placed on portions of HFST Sections 3 and 4, where failures had occurred. Plots of the SCRIM's friction and MPD data clearly show where these patches were placed (Figure 7.51). The HFST test sections returned the highest friction values (Figure 7.51A). The chip sealed pavement (Control) had the highest MPD, followed by the HFST test sections (Figure 7.51B).

Figure 7.51. Plots of the SCRIM's friction (A) and MPD (B) July 26, 2024, survey data



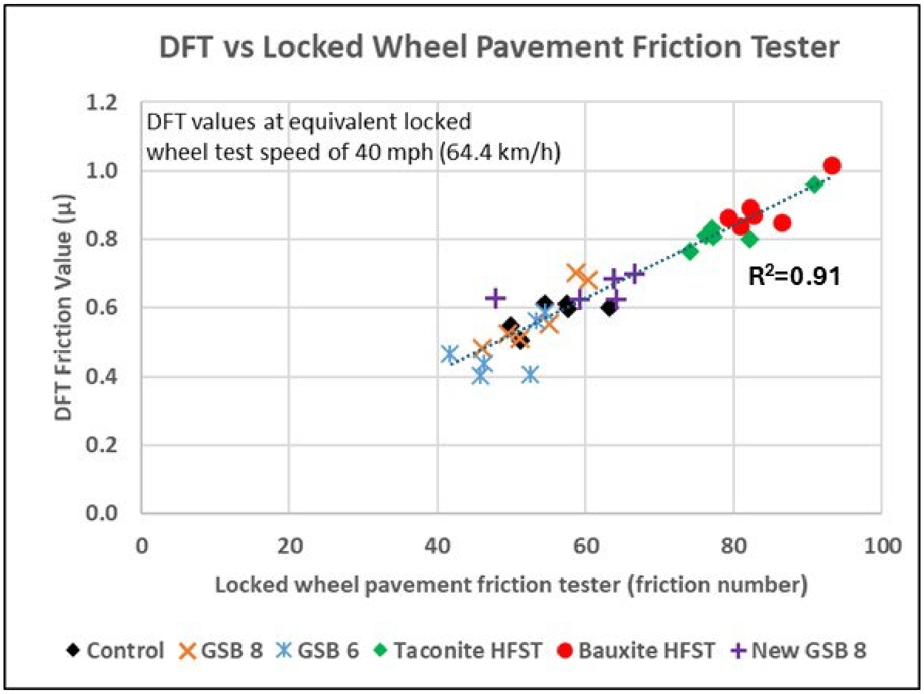
Because of its generally straight nature, the first 100 to 150 feet of the 2020 Bauxite HFST section (-1) could be considered analogous to the project's straight taconite and bauxite sections (3 and 4). As the SCRIM's data shows, the 2020 Bauxite HFST section's friction values were modestly lower than the project's taconite and bauxite test section's friction values. This finding suggests the 2020 Bauxite HFST section has exhibited a similar degree of wear under essentially the same traffic conditions that Test Sections 3 and 4 were subjected to.

7.4.3 Friction Testing: Key Findings

The project's primary focus – a comparison of taconite and calcined bauxite as aggregates in high friction surface treatment (HFST) applications – showed that taconite aggregate's friction numbers have averaged only ~6% lower than calcined bauxite's throughout the project and have exhibited virtually no divergence from calcined bauxite's numbers. This finding showed Taconite and calcined bauxite HFST test sections produced the highest friction numbers – on average about 40% to 50% higher than the chipseal control – as measured by the DFT and LWPFT.

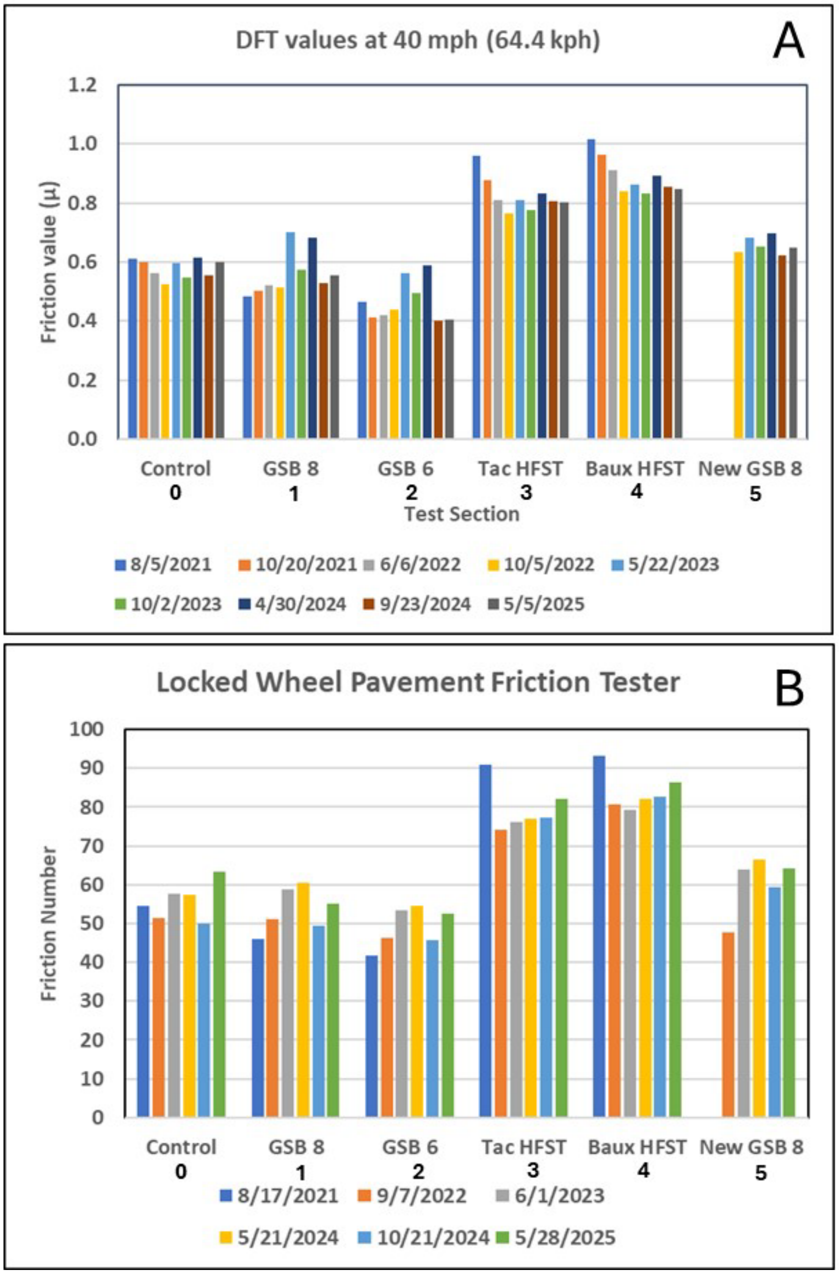
The LWPFT's skid numbers/friction numbers are well-correlated (R^2 of 0.91) with friction values generated by the DFT at the LWPFT's equivalent test speed of 40 mph (64.4 km/h), as Figure 7.52 shows. The correlation between the Control and two HFST installations is even higher (R^2 of 0.95). This relationship suggests that both friction measurement methods can be used interchangeably for generating comparable pavement friction assessment data in the field. The LWPFT's advantage is that it can perform testing quickly and "on the fly" and does not require traffic control. The DFT's advantages include its portability and that it can be used to assess short (<100 feet, or ~30 meter) segments of pavement and road intervals having high degrees of curvature (tight radii), two situations that are limiting to the LWPFT.

Figure 7.52. Plot of Dynamic Friction Tester vs Locked Wheel Pavement Friction Tester results through Spring of 2025



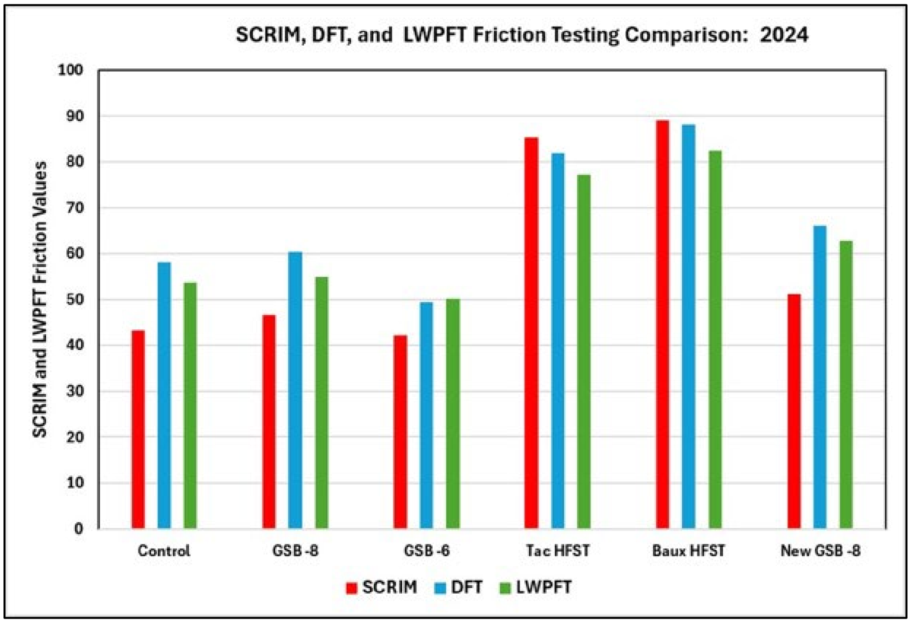
DFT and LWPF testing indicated a post-installation *increase* in the friction values of GSB -8 and GSB -6 (Sections 1 and 2) over time, through Spring of 2024, relative to their initial August 2021 (baseline) installation values (Figure 7.53). According to the contractor, this increase may have been reflective of gradual wear of the emulsion film that initially coated the surficial taconite aggregate particles embedded in the emulsion. Then, as the film abraded over time, and more and more of the embedded aggregate particle surfaces and angular edges became exposed, the pavement's friction characteristics slowly improved. Given that both test methods produced similar results for Test Sections 1 and 2 (and even to some degree for Test Section 5) this explanation seemed reasonable. The final two rounds of testing (Fall of 2024 and Spring 2025) showed that the GSB -8 and New GSB sections maintained their friction properties, but the GSB -6 test section (2) did not.

Figure 7.53. Complete Dynamic Friction Tester (A) and Locked Wheel Pavement Friction Tester (B) results



Overall, the friction values returned by the DFT, LWPFT, and SCRIM showed good agreement. Figure 7.54 plots the friction values for each measurement method made in 2024, with the LWPFT and DFT values being the average of their Spring and Fall 2024 testing dates, bracketing the SCRIM test date of July 26, 2024. ***NOTE:*** *The DFT's friction values, which typically range from 0.0 to 1.0, have been multiplied by 100 for better visualization.*

Figure 7.54. Comparison of SCRIM, DFT, and LWPFT 2024 friction values



Plots of SCRIM vs LWPFT (Figure 7.55A) and SCRIM vs DFT (Figure 7.55B) further illustrate how the respective friction measurement methods are well-correlated.

Figure 7.55. SCRIM friction testing results plotted against the LWPFT (A) and DFT (B)

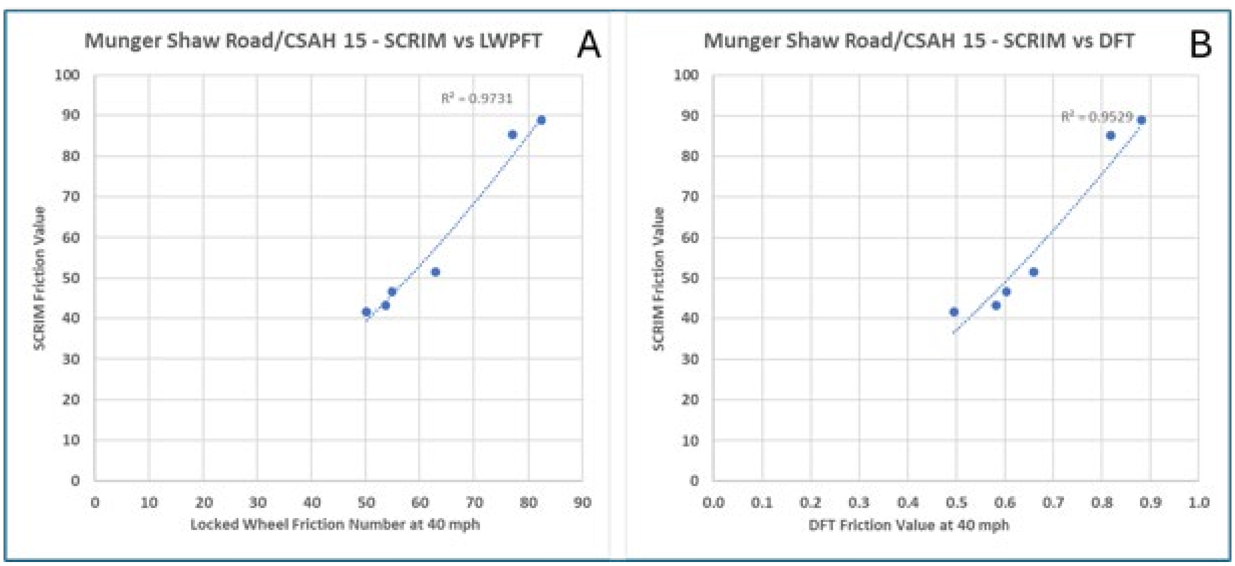
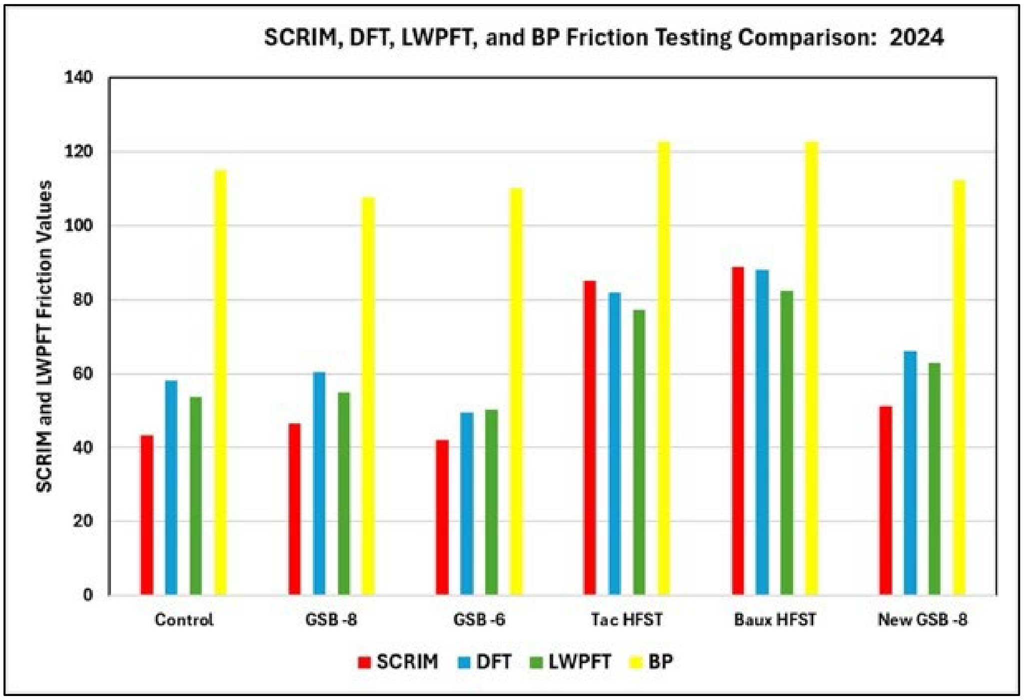


Figure 7.56 includes the British Pendulum's friction values and shows the BP having similar but more subdued agreement with the other three testing methods.

Figure 7.56. Comparison of SCRIM, DFT, LWPFT, and BP 2024 friction values



7.5 Life Cycle Assessment (LCA) of Taconite and Bauxite HFST

At the request of the project's co-investigator, the NRRI's Matthew Aro conducted a preliminary screening cradle-to-gate life cycle assessment (LCA) of high friction surface treatments (HFST) manufactured from calcined bauxite and taconite tailings. The potential environmental impacts of a) full HFST systems using both aggregate types (including the resin used); and b) calcined bauxite and taconite aggregate production alone, were compared. Aro's complete report is included as Appendix G.

The LCA was requested because calcined bauxite is typically produced overseas (e.g., China, Guyana) by heating bauxite up to 1600° to 1650° C (2900° to 3000° F), whereas taconite friction aggregate is produced by simply drying and screening taconite tailings to the meet the HFST specification. Furthermore, calcined bauxite is considered a preferred aggregate by FHWA for HFST applications. Therefore, it was believed that a preliminary screening LCA would provide additional insights for the current project.

Two figures from Aro's report summarize its key findings. Figure 7.57 is the LCA comparison of a taconite and bauxite HFST system. The epoxy resin impact used to bind the aggregate accounts for nearly 95% of total impacts in each impact category. A taconite HFST system had between 55% (Ecosystems) and 31% (Resources) fewer impacts across all impact categories than an HFST system using calcined bauxite.

Figure 7.57. LCA comparison of a taconite and bauxite HFST system

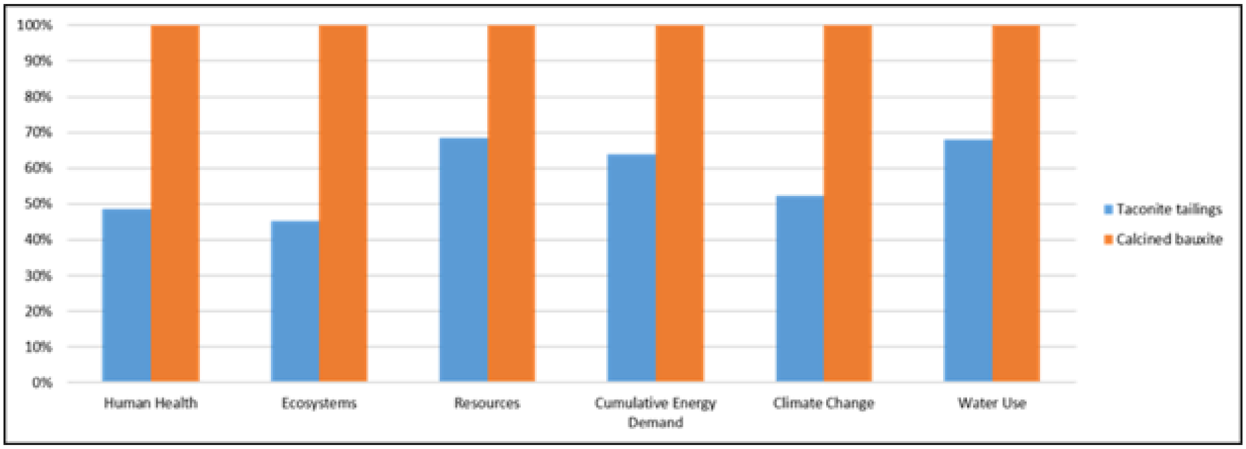
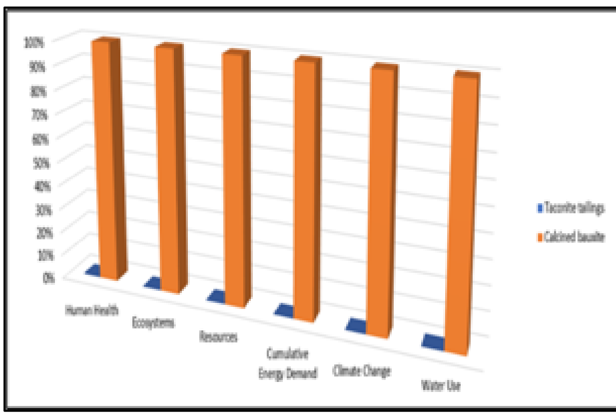


Figure 7.58 is an LCA comparison of a taconite and bauxite HFST aggregate production alone.

Figure 7.58. Comparative analysis of 1 ton of taconite tailings aggregate and calcined bauxite aggregate



Calcined bauxite impacts:

Human Health	2,807	x greater than taconite
Ecosystems	2,483	x greater than taconite
Resources	899	x greater than taconite
Cumulative Energy	2,265	x greater than taconite
Climate Change	2,899	x greater than taconite
Water Use	171,250	x greater than taconite

Figure 7.58 shows that the environmental impact of taconite friction aggregate production was found to be 2 to 3 orders of magnitude lower than that of calcined bauxite aggregate production.

7.6 Conference Presentations

On May 18, 2022, the former project PI, Larry Zanko, made a presentation to the Minnesota Transportation Conference & Expo in St. Paul, MN, titled: *"Taconite Mining Materials: An Overview of Past and Current Research, Challenges, and Potential Opportunities"*. The presentation included a brief overview of the project. Additional conference presentations specific to the project took place during Task 7B. Zanko also traveled to Washington DC to attend the TRB 102nd Annual Meeting and presented project findings to two project-relevant committees: AKT30 (Pavement Maintenance) on January 9, and AKM80 (Aggregates) on January 11, 2023.

On May 30, 2024, project co-Investigator, Larry Zanko, and Sara Post of NRRI made a presentation to the Minnesota Transportation Conference & Expo in St. Paul, MN, titled: *"Taconite as a Lower Cost Alternative High Friction Surface Treatment (HFST) to Calcined Bauxite for Low Volume Roads in Minnesota"*. On August 26, 2024, Ms. Post made a presentation to the Transportation Research Board's (TRB) Transportation Symposium on Environment, Energy, and Livable Economies, held in Denver, CO, titled: "*High-friction surface treatment using taconite tailings"*. Project co-investigator, Professor Manik Barman, traveled to Washington, DC, to attend the Transportation Research Board (TRB) 104th Annual Meeting, and made a presentation about the project to the Standing Committee on Pavement Surface Properties and Vehicle Interaction (AKP50) on January 8, 2025. And on April 8, 2025, Sara Post of NRRI presented, *"Taconite as a lower cost alternative High Friction Surface Treatment (HFST) to Calcined Bauxite for low volume roads in Minnesota"*, to The Geology of Emerging Mineral Opportunities session of the 2025 Society for Mining, Metallurgy and Exploration (SME) Minnesota Conference in Virginia, MN.

Chapter 8: Summary, conclusions and recommendations

The first year of post-installation friction testing and monitoring, is summarized as follows:

1) The bauxite and taconite HFST test sections had the highest friction numbers – more than 50% higher than the chipseal Control – with the bauxite HFST having the highest friction values.
2) The two GSB-based test sections had friction numbers lower than the chipseal control.
   a. Follow-up discussions indicated that a calibration issue with the deployment equipment possibly led to an aggregate application rate that was too low relative to the liquid emulsion application rate. As a result, the GSB-based Friction Seal system contractor coordinated with the friction aggregate provider, the PI, and St. Louis County, to install a new test section during the summer of 2022.
3) The dynamic friction tester (DFT) measurements showed good correlation with MnDOT's Locked Wheel Pavement Friction Tester (LWPFT) and likely provides a closer representation of field conditions than does the British Pendulum (BP).
4) The June 6, 2022, post-snowplowing DFT measurements indicated somewhat lower friction values for the HFST and control sections compared to the pre-snowplowing 2021 measurements, whereas the GSB -8 test section showed a slight increase, perhaps due to more aggregate particles being exposed as the emulsion coating is slowly abraded over time.
5) Distresses/losses in the bauxite and taconite HFST test sections were observed and documented in the project's 2021 installations, as well as in the previously installed (2020) bauxite test section. Closer examination of the distresses in the field and of field-collected samples in June and July of 2022 suggests that pre-existing weaknesses in the underlying HMA pavement led to two mechanisms of failure: 1) at the interface between the chipseal and underlying HMA; and 2) within the HMA itself. Notably, the bond between the HFST and chipseal did not show any evidence of failure.
6) Analysis showed that MnDOT's Road Doctor data was too coarse to be used for micro-texture studies that would provide surface friction characteristics. However, it is believed that the Road Doctor can be used to collect thermal data at the project site in the summer and winter, to measure the ability of a pavement to absorb energy (and therefore heat) more readily from the sun, which could be a helpful indicator of a pavement treatment's potential to contribute to more efficient and effective deicing during the winter.
7) A presentation was made at the Minnesota Transportation Conference & Expo in St. Paul, MN, on May 18, 2022, during which the current project was briefly described. Future presentations focusing specifically on the current project were to be made as the project proceeded.

The final three years of post-installation friction testing and monitoring – through Spring of 2025 – are summarized as follows:

1) The taconite and calcined bauxite HFST test sections produced the highest friction numbers, about 40 to 50% higher than the chipseal control.
2) DFT and LWPFT results for the taconite and calcined bauxite HFST test sections and the control section were highly correlated (R^2 of 0.95).
3) Taconite's friction numbers averaged about 6% lower than calcined bauxite's throughout the project and exhibited virtually no divergence from calcined bauxite's friction numbers over time, suggesting the two aggregates wear and maintain their friction characteristics similarly.
4) Two of the GSB test sections produced friction numbers comparable to the control.
5) The BP results have exhibited greater variability and often showed weak to no correlation with the DFT results on an individual test and test section basis. However, a comparison of the BP's and DFT's composite average results (4+ years of data, all test sections) shows weak/fair to good correlation (R^2 of 0.26 to 0.59), depending on the time range compared within the 4-year project period.
6) The July 2024 SCRIM test results showed good agreement with the DFT and locked wheel pavement friction tester. Like the LWPFT, the SCRIM requires no traffic control. But unlike the LWPFT, the SCRIM can test short pavement intervals and horizontal curves.
7) A life cycle assessment (LCA) showed that an HFST system using taconite aggregate had between 55% (Ecosystems) and 31% (Resources) fewer impacts across all impact categories than an HFST system using calcined bauxite and showed that the environmental impact of taconite friction aggregate production was 2 to 3 orders of magnitude lower than that of calcined bauxite aggregate production. These LCA findings have potential implications relative to environmental product declaration (EPD) considerations.

Collectively, the project's findings suggest that taconite (Mesabi) aggregate can provide comparable friction performance to calcined bauxite and at a smaller environmental footprint. This gives end users an alternative pavement surface treatment (taconite aggregate) to consider in their decision-making processes, offering enhanced safety at more locations with potential raw material, operational and maintenance cost savings.

If possible, maintaining the project's CSAH 15 pavement treatment sections for continued testing after the current project ends should be considered for monitoring long-term (> 5 years) performance. We highly recommended that new test installations be made on horizontal curves having higher average annual daily traffic (AADT) and where tangential forces are greatest (i.e., where HFSTs are most often applied). In combination, both recommendations would provide ongoing and new testing platforms to generate additional quantitative data for further assessing the field performance of taconite friction aggregate over time.

We also recommended that an expected crash modification factor (CRM) be applied to and incorporated with future investigations into enhanced friction surface treatments (i.e., relate CRM to friction data, rather than focusing solely on friction numbers). For example, the objective of a recent PennDOT and Penn State University study (Gayah et al., 2023) was to develop *"…a suite of crash modification factors (CMFs) to quantify the safety impacts of installing high-friction surface treatments (HFSTs) on horizontal curves and intersections within the Commonwealth of Pennsylvania."*

The July 2024 demonstration of SCRIM technology showed that it can generate detailed friction and pavement texture information over short distances and along horizontal curves, a testing methodology and capability that future projects should consider incorporating into their work plans. Another potentially useful aggregate material assessment and comparison tool to consider using on future related projects is the UMN Department of Civil, Environmental, and Geo-Engineering's advanced particle analyzer.

And going forward, taconite friction aggregate should probably be referred to something other than an HFST material because, for all practical purposes, the HFST classification (or "brand") essentially applies to calcined bauxite and because FHWA views calcined bauxite as such (Merritt et al., 2021). The minimum Al_2O_3 requirement that has been written into HFST spec sheets is instructive on this point because no other natural aggregate material can possibly meet that minimum spec other than calcined bauxite. Therefore, referring to taconite as – for example – an "Enhanced Friction Treatment (EFT)" alternative to HFST should be considered as a future descriptor.

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Appendix A: June 3, 2020, Kickoff Technical Advisory Panel (TAP) Meeting Note

Taconite as a lower cost alternative High Friction Surface Treatment to Calcined Bauxite for low volume roads in Minnesota

SUMMARY:

This was the project Kickoff Technical Advisory Panel (TAP) meeting. The objective of this meeting was to review and discuss the project and work plan. The attendees were:

Tracey Von Bargen (TL) – Grant County

Larry Zanko (PI) – UMD, NRRI

Naomi Eckerd – MnDOT State Aid

Mihai Marasteanu (Co-PI) – U of M

Morris Luke – MnDOT District 1

Manik Barman (Co-PI) – UMD Victor Lund – St. Louis County Public Works

Ryan Sutherland – Itasca County

William Wilde – Texas State University

Dave Glyer (PC) – MnDOT Research and Innovation

MEETING NOTES:

- Dave led introductions and gave a review of the project roles
    - Dave will manage the day-to-day aspects of the project and the Project Advisor, Brent Rusco, will step back but still be available if needed
- Tracey reiterated the purpose and need for the project:
    - Provide increased friction over traditional treatments on sharper horizontal curves
    - Utilize locally available materials that are effective and low cost
    - Application intended for 1,000 or less ADT
    - Group discussion regarding other High Friction Surface Treatment (HFST) sites in the Metro area as well as in Wisconsin
- Larry reviewed the project tasks, work plan and milestones
- Group discussion regarding the coordination of efforts with other agencies (MnDOT)
    - Victor helped locate an alternate testing site as the CSAH-8 site had sub-optimal pre- existing pavement conditions
        - Larry provided photos and other information for the new site on CSAH-15
        - in St. Louis County at curve #015D
        - Current site has a chip seal that will need to be removed prior to the application of the HFST
        - The site will be micro milled to get down to the original pavement surface

    - Victor indicated the Contractor is out of PA and will do the work (most likely) early August regardless of when the experimental treatment is ready to be applied
    - Victor also noted there was a window of around a month from micro milling to experimental treatment application
- Dave advised the TAP to let him know if there are any issues or delays that arise from Covid-19 restrictions and/or limitations
- Dave discussed a communication plan to share research results
  - Research and Innovation has a Marketing and Communication group that can help create a variety of methods to share this research and the research results
  - It was suggested that video should be taken of the test site at different project stages, especially during HFST application – Dave and Larry to discuss
  - It was also suggested to look into inviting local city and county engineers, contractors or members of pavement groups/associations for a test site visit
- Larry had a few discussion topics:
  - Locked wheel skid testing and related budget adjustments in light of new project location
    - Due to the shift in location, there may need to be budget changes as Mihai's and Manik's roles may be increased for field testing
  - Aggregate moisture spec for HFST test cells: the resin provider suggests a higher spec (in the 0.25% to 0.35% range) can be tolerated
    - Sika, the resin provider, is donating the epoxy resin liquid binder for this research project
    - Larry wondered if he should get something in writing from Sika regarding the higher spec but Victor did not think that was necessary
  - Potential 50:50 blend of taconite and bauxite: how could this be done?
    - Discussion of benefits
      - This is a darker treatment than calcined bauxite
      - There would be a solar gain from the darker material
  - Timing of asphaltic cells, microsurfacing
    - This needs to be coordinated so the donated epoxy resin liquid binder is delivered to the Contractor when it is needed
    - As noted earlier, the HFST does not need to be applied immediately to the milled surface
- Group discussion regarding friction testing at different stages of the project:
  - Plow blades are the biggest cause of treatment wear
    - To measure this effect, friction testing could be done in the fall, spring and

then again the following fall

            - This could provide additional information on winter wear vs. summer wear

        - It was also suggested to do the friction testing in the wheel path as well as the center of the treated road segment to measure what tire wear does to the HFST

        - Additionally, it was suggested to do a friction test of the milled surface and, at the same time, on a nearby chip seal surface
            - The intent would be to gather additional points of data

- Dave reviewed the next steps
    - The work plan will go through the contracting process – anticipating execution in mid-July
        - Project work cannot start before the contract is executed
    - First project Tasks are due for hand-in 8/31/2020
        - Task 1: Initial Memo on Expected Research Benefits and Potential Implementation Steps

        - Task 2: Literature Review
- There were no further comments or questions, so the meeting was adjourned

ACTION/FOLLOWUP ITEMS:

- Further discuss inviting local city and count engineers, contractors or members of pavement groups/associations for a test site visit – Larry/Tracey/Victor
- Meeting minutes to TAP - Dave
- Check on the possibility of recording video of the test site at different project stages - Dave/Larry
- Complete coordination of contractors and other agencies needed to complete the project – Larry/Tracey/Victor
- Notify the TAP when the contract is executed – Dave (mid-July?)

Appendix B: St. Louis County's summer of 2020 HFST installation program

(2356) HIGH FRICTION SURFACE TREATMENT

DESCRIPTION

This work consists of all labor, tests, materials, and equipment required for cleaning/preparing pavement surfaces, including full roadway width on bridge decks and approaches, and applying at a minimum of one coat of high friction surface treatment (HFST) to enhance skid resistance. The HFST consist of a binder resin system covered with a layer of calcined bauxite aggregate.

MATERIALS

Furnish uncontaminated materials of uniform quality that meets the requirements of the plans and specifications.

A. Binder Resin System

The polymeric resin binder shall consist of a two-part thermosetting polymer resin compound which holds the aggregate firmly in position and meet the requirements in Table 2356-1:

Table B.1. Polymetric resin binder requirements

Table 2356-1 Resin Binder Properties

Property	Requirements	Test Methods[1]
Viscosity, poises	7-30	ASTM D2556[2]
Gel Time, minutes	10 min	AASHTO M 235M/M235[3]
Ultimate Tensile Strength, psi	2,500-5,000	AASHTO M 235M/M235[4]
Elongation at Break, %	30-70	AASHTO M 235M/M235[5]
Compressive Strength, psi	1,000 min @ 3 hrs 5,000 min @ 7 days	ASTM C 579[6]
Water Absorption, %	1 max	AASHTO M 235M/M235[7]
Durometer Hardness (Shore D)	60-80	ASTM D 2240[8]
Cure Rate, hr	3 max	ASTM D1640/D1640M[9]
Adhesive Strength, psi	250 @ 24 hrs or 100% substrate failure	ASTM D4541[10]
Compressive Modulus of Elasticity, psi	130,000 min	ASTM C881 Type III
Thermal Compatibility	No Delamination	ASTM C884

1. Prepare all samples per manufacturer’s recommendation and perform tests at 73 ± 2ºF [23 ± 1ºC].
2. Viscosity - Prepare a 1-pt sample per manufacturer’s recommendations and mix for 2-3 min before testing. Use ASTM 2556 Appendix X1.1 for spindle selection.
3. Gel Time - Prepare a 60-g sample per manufacturer’s recommendation.

4. Ultimate Tensile Strength – Prepare Type 1 specimens in accordance with ASTM D638.
5. Elongation at Break - Prepare Type 1 specimens in accordance with ASTM D638. Cure specimen for 7 days at 73 ± 2ºF [23 ± 1ºC] and 50 ± 2ºF [10 ± 1ºC].
6. Compressive Strength - Prepare specimen according to Method B, 2- x -2in. cube, using 2.75 parts of sand to one part of mixed polymer resin binder by volume. Sand shall meet ASTM C778 for 20-30 sand. Cure specimens for 3 hours and 7 days at 73 ± 2ºF [23 ± 1ºC] and 50 ± 2ºF [10 ± 1ºC].
7. Water Absorption - Cure specimens for 7 days at 73 ± 2ºF [23 ± 1ºC] and 50 ± 2ºF [10 ± 1ºC].
8. Durometer Hardness - Prepare sample as per manufacturer's recommendation. Use the Type 1 Precision—Type D Durometer Method. Cure specimens for 7 days at 73 ± 2ºF [23 ± 1ºC] and 50 ± 2ºF [10 ± 1ºC].
9. Cure Rate - Prepare a specimen of 50-55 wet mil thickness. Cure specimens for 3 hours maximum at 73 ± 2ºF [23 ± 1ºC] and 50 ± 2ºF [10 ± 1ºC].
10. Adhesive Strength - Use method D, E, or F with a 2-in. loading fixture. Cure specimens for 3 hours maximum at 73 ± 2ºF [23 ± 1ºC] and 50 ± 2ºF [10 ± 1ºC].

B. Calcined Bauxite Aggregate

Furnish calcined bauxite aggregates that are fractured or angular in shape; resistant to polishing and crushing; clean and free of surface moisture; free from silt, clay, asphalt, or other organic materials; compatible with the resin binder; and meet the property and gradation requirements in Table 2356-2.

Table B.2. Furnish calcined bauxite aggregates requirements

Table 2356-2 Aggregate Properties

Property	Requirements	Test Method
Resistance to Degradation, %	20 max	AASHTO T 96[1]
Moisture Content, %	0.2 max	AASHTO T 255
Aluminum Oxide, %	87 min	ASTM C25[2]
Gradation Sieve Size No. 4 No. 16	Mass % Passing 100 min 5 max	AASHTO T 27

1. Use Grading D from Table 1.
2. Per section 15 for Aluminum Oxide.

The aggregates that will be used for the current project – calcined bauxite and Mesabi friction aggregate (taconite) – will follow the requirements shown in Table 2356-2. The exception will be the % aluminum oxide requirement, which only calcined bauxite aggregate can meet because of its chemical composition. And based on input from a potential resin provider, some easing of the moisture content requirement may also be allowed (e.g., up to 0.25%).

Appendix C: Two-part resin product information sheets for HFST

Sikadur® -22 Lo-Mod

BUILDING TRUST

PRODUCT DATA SHEET

Sikadur®-22 Lo-Mod

LOW-MODULUS, MEDIUM-VISCOSITY, EPOXY RESIN BINDER

PRODUCT DESCRIPTION

Sikadur®-22 Lo-Mod is a 2-component, 100 % solids, moisture-tolerant, epoxy resin binder. It conforms to the current ASTM C-881, Type III, Grade-2, Class-C and AASHTO M-235 specifications.

USES

Sikadur®-22 Lo-Mod may only be used by experienced professionals.
Use neat as the binder resin for a skid-resistant broadcast overlay. Use also as the binder resin for epoxy mortar and concrete for patching and overlays.

CHARACTERISTICS / ADVANTAGES

- Tolerant to moisture both before and after cure.
- Convenient easy mix ratio A:B = 1:1 by volume.
- Excellent strength development.
- Leveling viscosity for easy, efficient application of a broadcast overlay.
- Material is USDA-certifiable.

PRODUCT INFORMATION

Packaging	4 gallon units / 110 gallon unit / 660 gallon totes. Note: Part A of the Sikadur 22 Lo-Mod, Sikadur 22 LoMod FS and Sikadur 21 Lo-Mod LV is a universal component of these three products.
Color	Clear to light amber.
Shelf Life	2 years in original, unopened containers.
Storage Conditions	Store dry at 40–95 °F (4–35 °C). Condition material to 65–85 °F (18–29 °C) before using.
Viscosity	Approximately 2,000 cps.

TECHNICAL INFORMATION

Compressive Strength

	40°F* (4°C)	Mortar 1:3 73°F * (23°C)	90°F* (32°C)	Neat 73°F* (23°C)
8 hour	-	1,900 (13.1)	2,800 (19.3)	-
16 hour	-	4,300 (29.6)	5,000 (34.5)	1,850 (12.8)
1 day	2,200 (15.2)	5,200 (35.9)	5,200 (35.9)	2,600 (17.9)
3 day	6,500 (44.8)	6,800 (46.9)	5,900 (40.7)	6,200 (42.7)
7 day	7,900 (59.5)	7,200 (49.6)	6,100 (42.1)	6,800 (46.9)
14 day	8,800 (60.7)	7,600 (52.4)	6,100 (42.1)	7,000 (48.3)
28 day	9,500 (65.5)	7,900 (54.5)	6,100 (42.1)	7,200 (49.6)

* Material cured and tested at the temperatures indicated.

Property	Age	Value	Test / Conditions
Modulus of Elasticity in Compression	28 day	6.6 x 10^4 psi (455 MPa)	(ASTM D-695) 73 °F (23 °C) 50 % R.H.
Tensile Strength	14 days	5,700 psi (39.3 MPa)	(ASTM D-638) 73 °F (23 °C) 50 % R.H.
Tensile Modulus of Elasticity	14 days (Neat tested @ 0.5 in/min.)	1.9 x 10^5 psi (1,310 MPa)	(ASTM D-638) 73 °F (23 °C) 50 % R.H.
Elongation at Break	14 days	>30 %	(ASTM D-638) 73 °F (23 °C) 50 % R.H.

Property		Mortar 1:3	Neat	Test / Conditions
Tensile Adhesion Strength	7 days	510 psi concrete fail	570 psi concrete fail	ASTM C1583; ACI 503) 73 °F (23 °C) 50 % R.H.
Shear Strength	7 days	3,000 psi (22.7 MPa)	5,700 psi (37.2 MPa)	(ASTM D-732) 73 °F (23 °C) 50 % R.H.
Abrasion Resistance	14 days Weight loss, 1,000 cycles	1.8 gm (H-22 wheel; 1,000 gm weight)	.030 gm (CS-17 wheel; 1,000 gm weight)	(Taber Abrader) 73 °F (23 °C) 50 % R.H.
Water Absorption	7 days	(24 hour immer-sion)	Neat 0.26 %	(ASTM D-570) 73 °F (23 °C) 50 % R.H.

APPLICATION INFORMATION

Mixing Ratio	Component 'A':Component 'B' = 1:1 by volume.
Coverage	1 gal. yields 231 in^3 **Mortar Binder** - 1 gal. of mixed Sikadur®-22 Lo-Mod with the addition of 3 gal. by loose volume of an oven dried sand, yields approximately 808 in^3 of epoxy mortar.
Pot Life	Approximately 30 minutes (200 gram mass).

Cure Time

Tack-Free Time		
40 °F (4 °C)	73 °F (23 °C)	90 °F (32 °C)
6-8 hours	5 hours	2.5 hours

Traffic Time: 24 hours

APPLICATION INSTRUCTIONS

SUBSTRATE PREPARATION

Surface must be clean and sound. It may be dry or damp, but free of standing water. Remove dust, laitance, grease, curing compounds, impregnations, waxes and any other contaminants.

Preparation Work: Concrete - Should be cleaned and prepared to achieve a laitance and contaminant free, open textured surface (CSP 3-4 as per ICRI) by blast cleaning or equivalent mechanical means.
Steel - Should be cleaned and prepared thoroughly by blast cleaning to white metal finish.

MIXING

Proportion equal parts by volume of Component 'A' and 'B' into clean pail. Mix thoroughly for 3 min. with Sika paddle on low-speed (400–600 rpm) drill until uniformly blended. Mix only that quantity that can be used within pot life. To prepare epoxy mortar - Slowly add 3 parts by loose volume of oven-dried sand to 1 part of mixed Sikadur®-22 Lo-Mod until uniform in consistency.

APPLICATION METHOD / TOOLS

Broadcast Overlay - Prime the prepared substrate with Sikadur®-22 Lo-Mod. While primer is still tacky, spread mixed Sikadur®-22 Lo-Mod with a 3/16 in. notched squeegee. When material levels, broadcast the oven-dried aggregate slowly allowing it to settle in the epoxy binder. Ultimately the broadcast aggregate should be applied to excess at a rate of 2 lbs./ft² Remove excess broadcast aggregate after epoxy has set. Priming is an optional step in the broadcast overlay applications.

Epoxy Mortar - Prime prepared substrate with mixed Sikadur® 22 Lo-Mod or Sikadur® 21 Lo Mod LV. While primer is still tacky, apply epoxy mortar by trowel or vibrating screed. Finish with finishing trowel. Priming is mandatory when using the 22 Lo Mod as an epoxy mortar.

LIMITATIONS

- Minimum substrate and ambient temperature 40 °F (4 °C).
- For on grade, split-slab and unvented metal pan deck, please consult Sika Technical Service regarding moisture limitations.
- Minimum age of concrete before application is 21–28 days depending upon curing and drying conditions.
- Do not use on exterior slab on grade.
- Maximum thickness 1/2 in. (13 mm) exterior exposed to thermal change.
- Do not dilute. Addition of solvents will prevent proper cure.
- Use oven-dried aggregates only.
- Material is a vapor barrier after cure.
- Not an aesthetic product. Color may alter due to variations in lighting and/or UV exposure.

BASIS OF PRODUCT DATA

Results may differ based upon statistical variations depending upon mixing methods and equipment, temperature, application methods, test methods, actual site conditions and curing conditions.

OTHER RESTRICTIONS

See Legal Disclaimer.

ENVIRONMENTAL, HEALTH AND SAFETY

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Sikadur® -22 Lo-Mod FS

BUILDING TRUST

PRODUCT DATA SHEET

Sikadur®-22 Lo-Mod FS

Low-modulus, fast setting, medium-viscosity, epoxy resin binder

PRODUCT DESCRIPTION

Sikadur®-22 Lo-Mod FS is a 2-component, 100% solids, moisture-tolerant, fast setting epoxy resin binder. It conforms to the current ASTM C-881, Type III, Grade 1, Class C and AASHTO M-235 specifications.

USES

Sikadur®-22 Lo-Mod FS may only be used by experienced professionals.

Use neat as the binder resin for a skid-resistant broadcast overlay. Use also as the binder resin for epoxy mortar and concrete for patching and overlays.

CHARACTERISTICS / ADVANTAGES

- Fast Setting for quick turn around
- Meets 3 h/1000 psi requirement when mixed as an epoxy mortar
- Tolerant to moisture both before and after cure
- Convenient easy mix ratio A:B = 1:1 by volume
- Excellent strength development
- Leveling viscosity for easy, efficient application of a broadcast overlay
- Successfully used in HFST applications. Refer to local DOT specifications for product acceptance

PRODUCT INFORMATION

Chemical Base	Epoxy Resin
Packaging	4 gallon (15 L) units / 110 gallon (416 L) unit / 660 (2498 L) gallon totes. **Note: Part A of the Sikadur® 22 Lo-Mod, Sikadur®-22 Lo-Mod FS and Sikadur® 21 Lo-Mod LV is a universal component of these three products.**
Color	Clear to light amber
Shelf Life	24 months in original, unopened containers
Storage Conditions	Store dry at 40–95 °F (4–35 °C) Condition material at 65–85 °F (18–29 °C) before using.
Volatile organic compound (VOC) content	<20 g/L
Viscosity	Approximately 2,000 cps

TECHNICAL INFORMATION

Shore D Hardness	72				(ASTM D-2240) 73 °F (23 °C) 50 % R.H.

Compressive Strength (ASTM C-579)

	40 °F(4 °C)	73 °F (23 °C)	90 °F (32 °C)
3 hours	-	1750 psi	3600 psi
8 hours	2000 psi	4400 psi	6400 psi
1 day	4500 psi	6500 psi	8000 psi
3 days	5500 psi	7500 psi	8500 psi
7 days	8500 psi	8500 psi	9000 psi
14 days	9000 psi	9000 psi	9000 psi
28 days	9000 psi	9000 psi	9000 psi

Material cured and tested at the temperatures indicated and 50 % R.H.

Modulus of Elasticity in Compression (ASTM C-579) 73 °F (23 °C) 50 % R.H.

7 days	40,000 psi
28 days	40,000 psi

Tensile Strength (ASTM D-638) 73 °F (23 °C) 50 % R.H.

	Mortar 1:3	Neat
7 day	1200 psi	2650 psi

Elongation at Break (ASTM D-638) 73 °F (23 °C) 50 % R.H.

	Mortar 1:3	Neat
7 day	40 %	55 %

Tensile Adhesion Strength (ASTM C-1583; ACI 503R) 73 °F (23 °C) 50 % R.H.

	Mortar 1:3	Neat
1 day	-	> 550 psi (concrete failure)
7 days	-	> 570 psi (concrete failure)

Shear Strength (ASTM D-732) 73 °F (23 °C) 50 % R.H.

	Mortar 1:3	Neat
7 day	2600 psi	3430 psi

Thermal Compatibility Pass (ASTM C-884)

Abrasion Resistance (Taber Abrader) 73 °F (23 °C) 50 % R.H.

	Mortar 1:3	Neat
14 day, Weight loss, 1,000 cycles*	2.0 grams	0.030 grams

* (H-22 wheel; 1,000 gm weight for mortar/ C-17 wheel, 1,000 gm wt for neat)

Water Absorption (ASTM D-570) 73 °F (23 °C) 50 % R.H.

	Mortar 1:3	Neat
7 day (24 hour immersion)	-	< 0.20 %

Rapid Chloride Permeability 0 coulombs (AASHTO T-277)

APPLICATION INFORMATION

Mixing Ratio Component 'A': Component 'B' = 1:1 by volume.

Coverage 1 gal. yields 231 in³

Mortar Binder - 1 gal. of mixed Sikadur® 22 Lo-Mod FS with the addition of 5

	gal. by loose volume of an oven dried sand, yields approximately 808 cu. in. of epoxy mortar			
Pot Life	Approximately 15–20 minutes			(60 gram mass; ASTM C-881)
Waiting / Recoat Times		**60–64 °F (16-18 °C)**	**65–69 °F (19-21 °C)**	**70–74 °F (21-23 °C)**
	Coat 1	4–4 ½ h	2 ½–3 h	2–2 ½ h
	Coat 2	5 ½–6 h	4 ½–5 h	4 h
		75–79 °F (24-26 °C)	**80–84 °F (27-29 °C)**	**85+ °F (29+ °C)**
	Coat 1	2 h	1.5 h	1 h
	Coat 2	3 h	3 h	2 ½–3 h
	Average Substrate and Material Temperature. These set times were determined under laboratory conditions, actual set times may vary based on on-site conditions			

APPLICATION INSTRUCTIONS

SUBSTRATE PREPARATION

Surface must be clean and sound. It may be dry or damp, but free of standing water. Remove dust, laitance, grease, curing compounds, impregnations, waxes and any other contaminants.

Preparation Work: Concrete - Should be cleaned and prepared to achieve a laitance and contaminant free, open textured surface by blast cleaning or equivalent mechanical means.

Steel - Should be cleaned and prepared thoroughly by blast cleaning to white metal finish.

MIXING

Mixing Pre-mix each component. Proportion equal parts by volume of Component 'A' and 'B' into clean pail. Mix thoroughly for 3 min. with Sika paddle on low-speed (400–600 rpm) drill until uniformly blended. Mix only that quantity that can be used within pot life.

To prepare epoxy mortar - Slowly add 5 parts by loose volume of oven-dried sand to 1 part mixed resin.

APPLICATION METHOD / TOOLS

Broadcast Overlay - Prime the prepared substrate with Sikadur®-22 Lo-Mod FS. While primer is still tacky, spread mixed Sikadur®-22 Lo-Mod FS with a 3/16 in. (4.7 mm) notched squeegee. When material levels, broadcast the oven-dried aggregate slowly allowing it to settle in the epoxy binder.
Ultimately the broadcast aggregate should be applied to excess at a rate of 2 lb./ft² (0.9 kg/m²) Remove excess broadcast aggregate after epoxy has set. Priming is an optional step in the broadcast overlay applications.

Epoxy Mortar - Prime prepared substrate with mixed Sikadur®-22 Lo-Mod FS. While primer is still tacky, apply epoxy mortar by trowel or vibrating screed. Finish with finishing trowel. Priming is mandatory when using the Sikadur®-22 Lo-Mod FS as an epoxy mortar.

LIMITATIONS

- Minimum substrate and ambient temperature 40 °F (4 °C).
- Minimum age of concrete before application is 21–28 days depending upon curing and drying conditions.
- For on grade, split-slab and unvented metal pan deck, please consult Sika Technical Service regarding moisture limitations.
- Maximum thickness 1/2 in. (13 mm) exterior exposed to thermal change.
- Do not dilute. Addition of solvents will prevent proper cure.
- Use oven-dried aggregates only.
- Material is a vapor barrier after cure.
- Not an aesthetic product. Color may alter due to variations in lighting and/or UV exposure.
- For HFST applications, system and application details are governed by local DOT & AASHTO specification.

BASIS OF PRODUCT DATA

Results may differ based upon statistical variations depending upon mixing methods and equipment, temperature, application methods, test methods, actual site conditions and curing conditions.

OTHER RESTRICTIONS

See Legal Disclaimer.

ENVIRONMENTAL, HEALTH AND SAFETY

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Appendix D: Friction and Texture Testing of Aggregate used in High-Friction Surface Treatment (HFST) Application -- Bauxite, Taconite and 50/50 Blend - Ayesha Sha, North Central Superpave Center

Friction and Texture Testing of Aggregate used in High-Friction Surface Treatment (HFST) Application Bauxite, Taconite and 50/50 Blend

Conducted by: North Central Superpave Center
1205 Montgomery Street West Lafayette, IN
47906

Ayesha Shah

04 October, 2021

INTRODUCTION

This report summarizes the results of testing the frictional properties and surface texture of high-friction surface treatment (HFST) application on concrete tiles (23” x 23” x 1”). The testing protocol is loosely based on Indiana Test Method ITM 221 (1). The test was performed by the North Central Superpave Center (NCSC) on samples provided by the University of Minnesota, Duluth. The procedure and equipment used for this testing are outlined below.

This test method was initially developed to screen candidate coarse aggregates for potential use in asphalt surface mixtures for traffic volumes greater than 10,000,000 ESALs. Candidate aggregates that perform comparably to steel slag coarse aggregates or other approved control aggregates in this laboratory testing can then be used to construct a test section in the field if approved by INDOT.

BACKGROUND

Pavement friction depends on the macrotexture and microtexture of the surface. In a typical pavement, macrotexture is essentially the texture between and around the aggregates at the surface, while microtexture generally refers to the “roughness” of the aggregates themselves. The macrotexture is generally determined by the size and gradation of the aggregate blend used. The microtexture is a function of the type of aggregate, crystal size and structure (if crystalline), as well as other factors on the surfaces of the aggregates themselves.

Under the action of traffic, macrotexture can be lost as aggregates are abraded away or if traffic densification causes the matrix or binder to fill the “valleys” between aggregate particles. On the other hand, macrotexture can increase if aggregates are dislodged from the surface, creating small “craters” on the surface. Microtexture can change as the action of tires on the exposed aggregates polishes the surfaces; different types of aggregates can be more or less resistant to polishing.

MATERIALS

In this study, the friction and surface texture properties of high-friction aggregates used in surface treatment was evaluated. Bauxite is typically used in these HFST applications but tends to be expensive. An alternative aggregate source is derived from a naturally occurring iron ore called taconite. Davis (2) describes taconite as a hard, dense rock, composed largely of an intimate mixture of silicates and very fine magnetite (Fe_3O_4) crystals. Within the U. S., it is primarily mined from iron-ore formations in Minnesota (Mesabi range) and Michigan (Marquette range). A by-product of its processing - taconite tailings - is the source of the HFST aggregate used in this evaluation.

Figure D.1 shows the slabs prior to testing. The slabs shown in this figure contain the following surface treatments applied on three concrete tiles, from left to right, 50/50 blend of bauxite and taconite, 100% bauxite and 100% taconite.

Figure D.1. Test slabs with HFST application

TESTING METHODS AND EQUIPMENT

To simulate the effects of traffic moving over a surface, the friction samples were subjected to polishing. This simulation was produced by a polishing device, called a Circular Track Polishing Machine (CTPM), shown in Figure D.2, which consists of three rubber tires on a rotating plate that travel on the same footprint as the devices used to measure friction and texture (described below). The polishing wheels traveled at approximately 47 RPMs. Water was sprayed on the slab surface to help remove rubber particles that were abraded from the tires during polishing. A total of 300k wheel-passes were applied to each specimen.

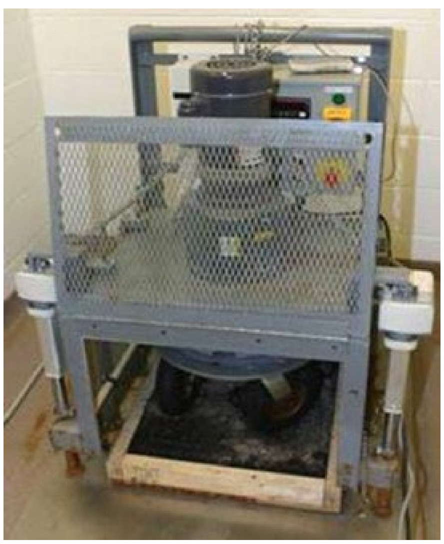


Figure D.2. Circular Track Polishing Machine (CPTM)

The surface texture and friction of each sample was measured periodically before and during polishing at 0, 3k, 9k, 30k, 75k, 150k, 225k and 300k wheel passes. The surface texture was measured using a laser-based Circular Track Meter (CTM) with a vertical resolution of 3 µm. The CTM is standardized in ASTM E2157 (3). The texture is reported here in terms of the Mean Profile Depth (MPD) in millimeters. The MPD has been shown to correlate very well to the Mean Texture Depth (MTD) measured with the sand patch test (3, 4).

The friction of each surface was measured using a Dynamic Friction Tester (DFT) according to ASTM E1911 (5). In the DFT, a disk with three rubber sliders attached rotates at tangential velocities up to 100 km/h (60 mph), then drops onto the surface: a starting point of 80 km/h is used here. The torque generated as the disk slows provides an indication of the friction at various speeds. The output from the DFT is the coefficient of friction (m) numbers at various speeds (typically 20, 40, 60 and 70 km/h (12, 25, 37 and 43 mph)). The DFT value at 20 km/h (12 mph), DFT20, is used with the MPD to calculate the International Friction Index (IFI) according to ASTM E1960 (6). The International Friction Index is represented by two parameters, the calibrated Friction Number (F60) and the calibrated Speed Constant (Sp) and shown as "IFI(F60, Sp)". The DFT and CTM are shown in Figure D.3.

The calibrated wet Friction Number, F60, is calculated using Equation 1 shown below.

$$F60 = 0.081 + 0.732DFT_{20}exp\left(\frac{-40}{S_p}\right) \quad (1)$$

where, the Sp (calibrated Speed Constant) is in km/h, given by Equation 2.

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

Figure D.3. Dynamic Friction Tester (left) and Circular Track Meter (right)

RESULTS

The results of testing these samples are tabulated in Table D.1 and illustrated in Figure D.4 to Figure D.6. Each MPD and DFT20 value is the average of two measurements.

Table D.1. Summary of Results

Wheel passes, x10^3	Bauxite			50/50 Bauxite-Taconite			Taconite		
	MPD, mm	DFT_{20}	F60	MPD, mm	DFT_{20}	F60	MPD, mm	DFT_{20}	F60
0	1.80	0.977	0.65	2.04	0.956	0.65	1.57	0.976	0.63
3	1.57	0.935	0.61	1.47	0.925	0.60	1.38	0.912	0.58
9	1.68	0.910	0.60	1.48	0.886	0.57	1.35	0.858	0.55

Wheel passes, $x10^3$	Bauxite			50/50 Bauxite-Taconite			Taconite		
	MPD, mm	DFT_{20}	F60	MPD, mm	DFT_{20}	F60	MPD, mm	DFT_{20}	F60
30	1.43	0.892	0.57	1.39	0.835	0.54	1.31	0.763	0.49
75	1.51	0.935	0.60	1.29	0.825	0.52	1.33	0.654	0.44
150	1.47	0.809	0.53	1.32	0.745	0.48	1.37	0.619	0.42
225	1.34	0.807	0.52	1.37	0.698	0.46	1.35	0.575	0.39
300	1.28	0.802	0.51	1.24	0.646	0.42	1.26	0.549	0.37

Figure D.4 illustrate the changes in the mean profile depth, as measured with the CTM. It can be seen that although bauxite and the 50/50 blended samples started off with slightly higher texture than taconite sample, the MPD values of all three slabs levelled off with increasing wheel passes, around 1.25 mm. Initial high values are typical of the rough texture of these treatment applications, which is worn down by the aggressive scrubbing action of the tires. Inspection of the slabs after completion of 300k wheel passes did not show excessive raveling in any of the test slabs. The terminal MPD values were within the desired range for pavement surfaces (0.25 mm < MPD <1.5 mm). The minor differences in MPD observed between the three test slabs do not greatly impact the IFI (F60, Sp). The IFI is more heavily influenced by DFT20 value, as can be seen from equations 1 and 2.

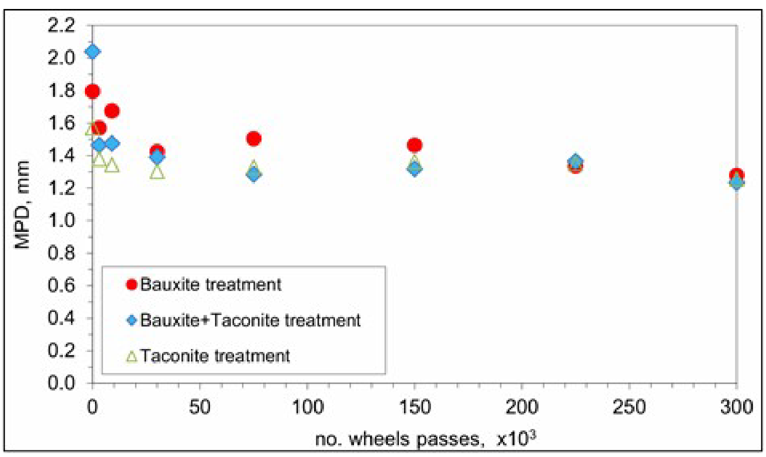


Figure D.4 Mean profile depth vs. wheel passes

Figure D.5 shows the dynamic friction reading at 20 kph, DFT20, versus wheel passes of the polishing machine. All the test samples showed a peak initial value due to the exposed aggregates on the surface, which are typical of new, unpolished specimens. With increasing polishing level (wheel passes), the differences in surface friction between the three samples became more apparent. Bauxite being the most aggressive aggregate, had the highest friction values throughout, followed by the bauxite-taconite blend and lastly, taconite. While the wet friction number of bauxite plateaued at 150k wheel passes, that of taconite and the blended aggregate appear to be still decreasing even at the completion of 300k wheel passes. However, the end friction number of all three materials is still high and well within the desired range for pavements (0.30 < DFT20 < 0.90). The increase in DF20 value at 75k observed for bauxite sample may be attributed to the use of new DFT sliders (and new tires) at this point.

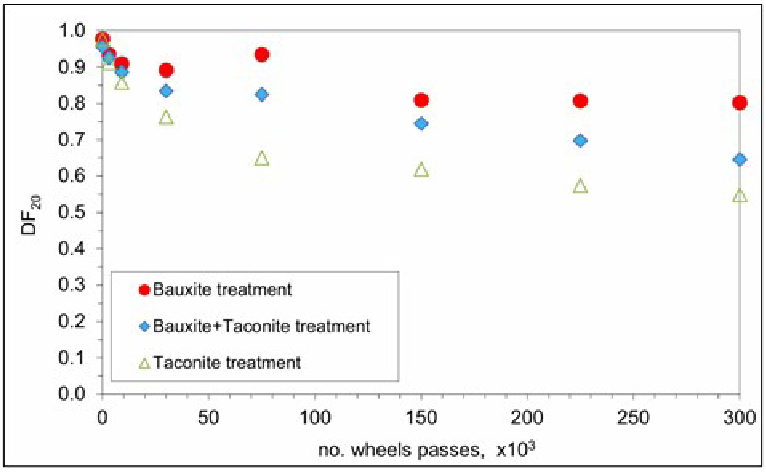


Figure D.5 DFT_{20} vs. wheel passes

Finally, Figure D.6 shows the calculated wet friction number (F60) versus wheel passes. The trends and similarity in shape of the graphs observed between Figure D.5 and Figure D.6 confirm the earlier statement that DFT_{20} value has a greater impact on the IFI (F60, Sp) value than the MPD value. The observed trends reflect the composition of samples tested, with pure bauxite sample having the highest wet friction followed by the 50/50 bauxite + aconite and lastly, pure taconite. Overall, all samples performed well and did not exhibit excess raveling of the surface aggregate. The terminal MPD and DFT20 values were within the prescribed ranges (5).

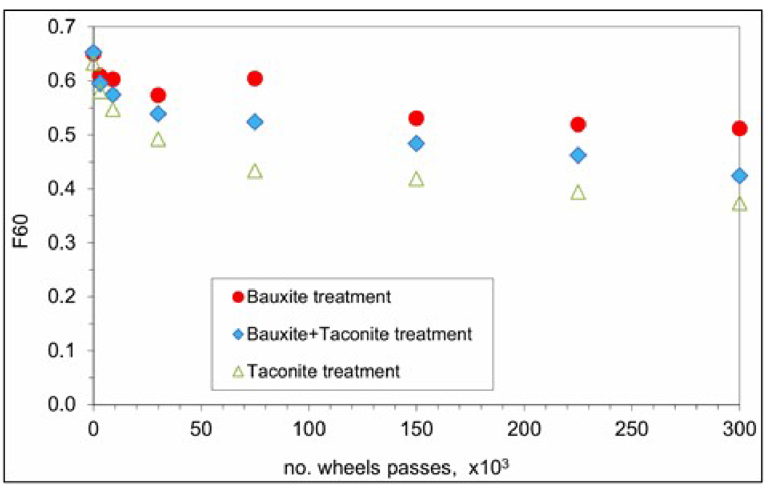


Figure D.6 F60 values vs. wheel passes

Figure D.7. 100% Bauxite-after testing

Figure D.8. 50/50 Bauxite + Taconite treatment-after testing

Figure D.9. 100% Taconite treatment-after testing

REFERENCES

Indiana Test Method 221-12P, Acceptance Procedures for HMA Surface Mixture Coarse Aggregates for ESAL ≥10,000,000.

Davis, Edward (1964). Pioneering with Taconite, Minnesota Historical Society, 246p.

ASTM E2157, Standard Test Method for Measuring Pavement Macrotexture Using the Circular Track Meter.

ASTM E1845, Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth.

ASTM E1911, Standard Test Method for Measuring Surface Frictional Properties Using the Dynamic Friction Tester.

ASTM E1960, Standard Practice for Calculating International Friction Index of a Pavement Surface.

Appendix E: Safety data sheets for HFST aggregate types

LKAB Minerals

Non-hazardous material safety data sheet for

Bauxite – calcined

This generic SDS is provided by LKAB Minerals to give information to assist with material handling of the products listed which are not classified as hazardous under the GHS and / or the CLP regulations.

SECTION 1: Identification of the substance/mixture of the company/undertaking

1.1 Product identifier

Product name:	Bauxite
Synonyms / trade names:	RASC Bauxite, Rotary (Rota) Bauxite, Round Kiln (RK) Bauxite REACH
registration number:	Exempt
CAS number:	92797-42-7
EC number:	296-578-9

1.2 Relevant identified uses of the substance or mixture and uses advised against

Identified uses: Refractory material

1.3 Details of the supplier of the safety data sheet

LKAB Minerals Ltd, Flixborough Industrial Estate, Flixborough, North Lincolnshire DN15 8SF UK minerals.sds@lkab.com

1.4 Emergency telephone number of supplier

LKAB Minerals AB (Sweden)	+46 771 760 400
LKAB Minerals Asia Pacific Ltd (Hong Kong)	+852 2827 3000
LKAB Minerals BV (Netherlands)	+31 168 388500
LKAB Minerals Inc (USA)	+1 513 322 5530
LKAB Minerals GmbH (Germany)	+49 201 45060
LKAB Minerals Ltd (United Kingdom)	+44 1724 277411 or +44 1332 673131
LKAB Minerals Oy (Finland)	+358 17 2660160
LKAB Minerals Tianjin (China)	+86 22 2435 1706

Hours of operation: 09.00 – 16.00 (local business hours)

SECTION 2: Hazards identification

2.1 Classification of the substance or mixture

Classification (EC 1272/2008): Physical and chemical hazards: not classified
Human health: not classified Environment: not classified
Classification (67/548/EEC): Not classified
The full text for all R-phrases and hazard statements are displayed in section 16.

2.2 Label elements

EC No: 296-578-9
Label in accordance with (EC) No. 1272/2008 No pictogram required.

2.3 Other hazards

This product does not contain any PBT or vPvB substances.

SECTION 3: Composition/information on ingredients

3.1 Substances

Product / ingredient name	%	CAS No	EC No	Classification Regulation (EC) No. 1272/2008 [CLP]
Bauxite	99	92797-42-7	296-578-9	Not classified
Aluminium Oxide	>82	1344-28-1	215-691-6	Not classified
Quartz	<10	14808-60-7	238-878-4	Not classified
Titanium Oxide	<5	13463-67-7	236-675-5	Not classified
Iron (III) Oxide	<3	1309-37-1	215-168-2	Not classified

The full text for all R phrases and hazard statements are displayed in section 16. REACH

Registration number: Exempt

SECTION 4: First aid measures

4.1 Description of first aid measures

Inhalation: Move the exposed person to fresh air at once. Get medical attention if any discomfort continues.

Ingestion: Rinse mouth thoroughly. Get medical attention if any discomfort continues.

Skin contact: Wash skin with soap and water. Get medical attention if irritation persists after washing.

Eye contact: Make sure to remove any contact lenses from the eyes before rinsing. Rinse eye with water immediately. Get medical attention if any discomfort continues.

4.2 Most important symptoms and effects, both acute and delayed

Inhalation: No specific symptoms noted.

Ingestion: No specific symptoms noted.

Skin contact: No specific symptoms noted.

Eye contact: No specific symptoms noted.

4.3 Indication of any immediate medical attention and special treatment needed

Treat symptomatically

SECTION 5: Firefighting measures

5.1 Extinguishing media

This product is not flammable. Use fire extinguishing media appropriate for surrounding materials.

5.2 Special hazards arising from the substance or mixture

Hazardous combustion products: None under normal conditions

5.3 Advice for firefighters

Special fire fighting procedures: No specific fire fighting procedures given

SECTION 6: Accidental release measures

6.1 Personal precautions, protective equipment and emergency procedures

Follow precautions for safe handling described in this safety data sheet

6.2 Environmental precautions

The product should not be dumped in nature but collected and delivered according to agreement with the local authorities.

6.3 Methods and material for containment and cleaning up

Avoid dust formation. Remove spillage with vacuum cleaner. If not possible, collect spillage with shovel, broom or the like. Transfer to a container for disposal.

6.4 Reference to other sections

For personal protection see section 8. For waste disposal see section 13.

SECTION 7: Handling and storage

7.1 Precautions for safe handling

Avoid handling which leads to dust formation. Avoid inhalation of high concentrations of dust. Observe occupational exposure limits and minimise the risk of inhalation of dust.

7.2 Conditions for safe storage, including any incompatibilities

Store in tightly closed original container in a dry, cool and well-ventilated place. Keep in original container.

7.3 Specific end use(s)

The identified uses for this product are detailed in section 1.2

SECTION 8: Exposure controls / personal protection

8.1 Control parameters

Name	STD	TWA – 8hrs	STEL – 15mins	Notes
Aluminium Oxide	WEL	10 mg/m^3		
Iron (III) Oxide	WEL	5 mg/m^3	10 mg/m^3	as Fe
Quartz	WEL	0.1 mg/m^3		
Titanium Oxide	WEL	10 mg/m^3		

WEL = Workplace Exposure Limit

Ingredient comments:

Dust contains respirable crystalline silica. Prolonged and/or massive inhalation of respirable crystalline silica dust may cause lung fibrosis, commonly referred to as silicosis. Principal symptoms of silicosis are cough and breathlessness. Occupational exposure to respirable dust should be monitored and controlled. The product should be handled using methods and techniques that minimise or eliminate dust generation. The product contains less than 1% w/w RCS (respirable crystalline silica) as determined by the SWERF method. The respirable crystalline silica content can be measured using the "Size-Weighted Respirable Fraction – SWERF" method. All details about the SWERF method is available at www.crystallinesilica.eu

8.2 Exposure controls

Protective equipment

Engineering measures:	Provide adequate ventilation. Observe occupational exposure limits and minimise the risk of inhalation of dust.
Respiratory equipment:	the general level exceeds the recommended occupational exposure limit. Wear dust masks in dusty areas.
Hand protection:	No specific hand protection noted, but gloves may still be advisable.
Eye protection:	Wear dust resistant safety goggles where this is a danger of eye contact.
Other protection:	Provide eyewash station.
Hygiene measures:	Wash hands at the end of each work shift and before eating, smoking and using the toilet.

SECTION 9: Physical and chemical properties

9.1 Information on basic and physical and chemical properties

Appearance:	Granular powder, dust
Colour:	Grey
Odour:	Odourless
Solubility:	Insoluble in water
Melting point (°C):	2000
Relative density:	>3.1
9.2 Other information	Not relevant

SECTION 10: Stability and reactivity

10.1 Reactivity — No specific reactivity hazards associated with this product.

10.2 Chemical stability — Stable under normal temperature conditions.

10.3 Possibility of hazardous reactions — Not relevant

10.4 Conditions to avoid — No specific conditions are likely to result in a hazardous situation

10.5 Incompatible materials

Materials to avoid: No specific, or groups of materials, are likely to react to produce a hazardous situation.

10.6 Hazardous decomposition products — None under normal circumstances

SECTION 11: Toxicological information

11.1 Information on toxicological effects

Acute toxicity:	Not classified
Acute toxicity (Oral LD50):	No data available
Acute toxicity (Dermal LD50):	No data available
Acute toxicity (Inhalation LC50):	No data available
Skin corrosion/irritation:	Not classified. No data available.
Serious eye damage/irritation:	Not classified. No data available.
Respiratory or skin sensitisation:	Not sensitising. No data available.
Germ cell mutagenicity:	Not classified. No data available.
Carcinogenicity:	Not classified. (There is no evidence that the product can cause cancer)
Reproductive toxicity:	Not classified (This substance has no evidence of toxicity to reproduction)
STOT-single exposure:	Not classified as a specific target organ toxicant after a single exposure
STOT- repeated exposure:	Not classified as a specific target organ toxicant after repeated exposure
Aspiration hazard:	Not classified (Not anticipated to present an aspiration hazard, based on chemical structure)

SECTION 12: Ecological information

12.1Toxicity:	Not classified
12.2Persistence and degradability	No data available.
12.3Bioaccumulative potential:	No data available.
12.4Mobility in soil:	Not relevant, due to the form of the product.
12.5Results of PBT and vPvB assessment:	No data available.

SECTION 12: Ecological information

12.6 Other adverse effects: None known

SECTION 13: Disposal considerations

13.1 Waste treatment methods: Dispose of waste and residues in accordance with local authority requirements.

SECTION 14: Transport considerations

Road transport notes:	Not classified
Rail transport notes:	Not classified
Sea transport notes:	Not classified
Air transport notes:	Not classified

14.1 UN Number: The product is not covered by international regulation on the transport of dangerous goods (IMDG, IATA, ADR/RID).

14.2 UN proper shipping name: Not classified for transportation.

14.3 Transport and hazard class(es): Not classified for transportation.

14.4 Packing group: Not classified for transportation.

14.5 Environmental hazards Environmentally hazardous substances / marine pollutant: no

14.6 Special precautions for user: Not classified for transportation.

14.7 Transport in bulk according to Annex II of MARPOL73/78 and the IBC Code
Not applicable

SECTION 15: Regulatory information

15.1 Safety, health and environmental regulations / legislation specific for the substance or mixture

Approved code of practice:	Classification and labelling of substances and preparations dangerous for supply. Safety data sheets for substances and preparations.
Guidance notes:	Workplace Exposure Limits EH40.
EU Legislation:	Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulations (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC, including amendments. Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006 with amendments.

15.2 Chemical Safety Assessment: Not applicable. No chemical safety assessment has been carried out.

SECTION 16: Other information

Revision date:	29/05/2020
Revision:	5
Document no:	12-05EN,20-05
Risk phrases in full:	NC – not classified

Disclaimer:
This information relates only to the specific material designated and may not be valid for such material used in combination with any other materials or in any process. Such information is, to the best of the company's knowledge and belief, accurate and reliable as of the date indicated. However no warranty guarantee or representation is made to its accuracy, reliability of completeness. It is the user's responsibility to satisfy himself as to the suitability of such information for his own particular use.

SAFETY DATA SHEET

Version 1.0 Revision Date: 06/12/15

1. PRODUCT AND COMPANY IDENTIFICATION

1.1 Product identifiers

Product Name: Round Kiln (RD) and Rotary Kiln (RT) Calcined Bauxite Product Number: RD-88, RT-90 (multiple mesh and grit sizes)
Trade Name: Chinese Bauxite - Calcined
General Use: Refractory Material
Chemical Family: Bauxite
CAS-No: 92797-42-7
EC-No: 296-578-9

1.2 Relevant identified uses of the substance or mixture and uses advised against

Identified uses: Industrial Applications

1.3 Details of the supplier of the safety data sheet

Company: Great Lakes Minerals, 1200 Port Road
Wurtland, Kentucky 41144-1635 USA
Telephone: +1 (606) 833-8383
Email: CustomerService@glmin.com

1.4 Emergency telephone number

Emergency Phone #: + 1(606) 833-8383 (8:00am – 4:30pm EST)

2. HAZARDS IDENTIFICATION

2.1 Classification of the substance or mixture Component Classified – None

GHS Classification in accordance with 29 CFR 1910 (OSHA HCS)
Not Classified

2.2 GHS Label elements, including precautionary statements

Pictogram: Not applicable
Signal word: No signal word
Hazard statement(s): No known significant effects or critical hazards
Precautionary statement(s): Not applicable

2.3 Hazards not otherwise classified (HNOC) or not covered by GHS – none

3. COMPOSITION/INFORMATION ON INGREDIENTS

3.1 Substances

Synonyms: Calcined Bauxite
Formula: Mixture
Density (g/ml) 3.1 g/cc at 20°C

3.2 Ingredients

	CAS Number	EINECS Number	Percentage (%)
	1344-28-1 1302-93-8 12004-39-6 -----	215-691-6 215-113-2 234-456-9 ----	>80% WT 15% WT 4% WT <1% WT

3.3 Hazardous Components

None of the compounds in this mixture are shown to be hazardous under normal conditions of use

3.4 Additional Information

Per the XRD Rietveld Method used to determine mixture components and content, there are no additional ingredients present which, within the current knowledge of the supplier and in the concentrations applicable are significant or classified as hazardous to health or the environment and hence require reporting in this section.

4. FIRST AID MEASURES

4.1 Description of first aid measures

Inhalation: If adverse effects occur, remove to uncontaminated area. If not breathing, give artificial respiration or oxygen by qualified personnel. Seek immediate medical attention

Skin Contact: Wash skin with soap and water. If necessary, seek medical attention **Eye Contact:** Flush

eyes with water. If necessary, seek medical attention **Ingestion:** If a large amount is swallowed, get

medical attention

4.2 Most Important Symptoms/Effects, Acute and Delayed: No data available; generated dust may result in irritation.

4.3 Indication of any immediate medical attention and special treatment needed

No specific treatment. Treat symptomatically. Contact poison treatment specialist immediately if large quantities have been ingested or inhaled.

5. FIREFIGHTING MEASURES

5.1 Extinguishing media

This product is not flammable. Use fire extinguishing media appropriate for surrounding materials.

5.2 Special hazards arising from the substance or mixture

Hazardous combustion products: None under normal conditions

5.3 Advice for firefighters

Special fire-fighting procedures: No specific fire-fighting procedures given

6. ACCIDENTAL RELEASE MEASURES

6.1 Personal precautions, protective equipment and emergency procedures

Follow precautions for safe handling described in this safety data sheet

6.2 Environmental precautions

The product should not be dumped in nature but collected and delivered according to agreement with the local authorities.

6.3 Methods and material for containment and cleaning up

Avoid excessive dust formation. Transfer to a container for disposal.

6.4 Reference to other sections

For personal protection see section 8. For waste disposal see section 13.

7. HANDLING AND STORAGE

7.1 Precautions for safe handling

Put on appropriate personal protective equipment (see Section 8). Eating, drinking and smoking should be prohibited in areas where this material is handled, stored and processed. Workers should wash hands and face before eating, drinking and smoking. Remove contaminated clothing and protective equipment before entering eating areas.

7.2 Conditions for safe storage, including any incompatibilities

Store in accordance with local regulations.

8. EXPOSURE CONTROLS/PERSONAL PROTECTION

8.1 Exposure Limits:

ACGIH (TLV): 1 mg/m3 (TWA, respirable fraction, related to Aluminum insoluble compounds) OSHA

(PEL): 15 mg/m3 (TWA, total particulates, not otherwise regulated)

5 mg/m3 (TWA, respirable particulates, not otherwise regulated).

Engineering Controls: Provide adequate ventilation to control dusts. Observe occupational exposure limits and minimize the inhalation of dusts.

Respiratory Protection: No specific recommendation made, but respiratory protection must be used if the general dust level exceeds recommended occupational exposure limits. Wear appropriate dust masks in high dust conditions and affected work areas.

Eye/Face Protection: Wear dust resistant safety goggles where this is danger of eye contact. Provide eyewash station.

Skin and Body Protection: No specific hand protection noted, but gloves may still be advisable. Wash hands at the end of each work shift and before eating, smoking and using the toilet.

9. PHYSICAL AND CHEMICAL PROPERTIES

9.1 Information on basic physical and chemical properties

Physical state:	Granular solid. Powder
Color:	Tan / Grey
Melting point:	2000°C (3632°F)
Oder:	Odorless
pH:	Neutral
Relative density:	3.1 g/cc at 20°C
Granulometry:	Varies (Generally >1µm)

10. STABILITY AND REACTIVITY

10.1 Reactivity

Stable under normal temperature conditions.

10.2 Chemical stability

The product is stable.

10.3 Possibility of hazardous reactions

Under normal conditions of storage and use, hazardous reactions will not occur.

10.4 Conditions to avoid

None known.

10.5 Incompatible materials

No specific, or groups of materials, are likely to react to produce a hazardous situation.

10.6 Hazardous decomposition products

Under normal conditions of storage and use, hazardous decomposition products should not be produced.

11. TOXICOLOGICAL INFORMATION

11.1 Information on toxicological effects

Other health effects: This substance has no evidence of carcinogenic properties

Acute toxicity

Acute toxicity (Oral LD50): Not relevant Acute toxicity (Dermal LD50): Not relevant Acute toxicity (Inhalation LC50): Not relevant

Inhalation: Dust in high concentrations may irritate the respiratory system

Ingestion: May cause discomfort if swallowed

Skin contact: Powder may irritate skin

Eye contact: Particles in the eyes may cause irritation and smarting

12. ECOLOGICAL INFORMATION

Ecotoxicity: Not regarded as dangerous for the environment

12.1 Acute fish toxicity: Not considered toxic to fish

12.2 Persistence and degradability: The product is not readily biodegradable

12.3 Bioaccumulative potential: The product is not bioaccumulating

12.4 Mobility in soil: Not relevant, due to the form of the product

12.5 Results of PBT and vPvB assessment: This product does not contain any PBT or vPvB substances

12.6 Other adverse effects: None known

13. DISPOSAL CONSIDERATIONS

13.1 Waste treatment methods

Product

Dispose of waste and residues in accordance with local authority requirements

Contaminated packaging

Dispose of as unused product

14. TRANSPORT INFORMATION

Road transport notes: Not classified Rail transport notes: Not classified Sea transport notes: Not classified Air transport notes: Not classified

14.1 UN Number: The product is not covered by international regulation on the transport of dangerous goods (IMDG, IATA, ADR/RID)

14.2 UN proper shipping name: Not classified for transportation

14.3 Transport and hazard class(s): Not classified for transportation

14.4 Packing group: Not classified for transportation

14.5 Environmental hazards: Not an environmentally hazardous substance / marine pollutant

14.6 Special precautions for user: Not classified for transportation

14.7 Transport in bulk according to Annex II of MARPOL73/78 and the IBC Code Not applicable

15. REGULATORY INFORMATION SARA 302 Components

No chemicals in this material are subject to the reporting requirements of SARA Title III, Section 302

SARA 313 Components

The following components are subject to reporting levels established by SARA Title III, Section 313: Aluminum Oxide CAS-No. 1344-28-1 Revision Date: 1994-04-01

SARA 311/312 Hazards

Regulated per OSHA HAZCOM Standards

Massachusetts Right to Know Components

Aluminum Oxide	CAS-No. 1344-28-1	Revision Date: 1994-04-01

Pennsylvania Right to Know Components

Aluminum Oxide	CAS-No 12004-39-6	Revision Date: 1994-04-01

New Jersey Right to Know Components

Aluminum Oxide	CAS-No. 1344-28-1	Revision Date: 1994-04-01
Aluminum Silicate	CAS-No. 1302-93-8	
Titanium Aluminum Oxide	CAS-No 12004-39-6	

California Prop. 65 Components

This product does not contain any chemicals known to the State of California to cause cancer, birth defects, or any other reproductive harm.

16. OTHER INFORMATION

Full text of H-Statements referred to under sections 2 and 3.

Not applicable

HMIS Rating

Health hazard:	1
Chronic Health Hazard: Flammability:	* 0
Physical Hazard	0

NFPA Rating

Health hazard:	1
Fire Hazard:	0
Reactivity Hazard:	0

Further information

License granted to make unlimited paper copies for internal use only. The above information is believed to be correct but does not purport to be all inclusive and shall be used only as a guide. The information in this document is based on the present state of our knowledge and is applicable to the product with regard to appropriate safety precautions. It does not represent any guarantee of the properties of this product due to naturally occurring variation in the ore from time to time. Great Lakes Minerals and its Affiliates shall not be held liable for any damage resulting from handling or from contact with the above product.

Safety Data Sheet (SDS)

Section 1 – Identification

1(a) Product Identifier Used on Label: Taconite Tailings
1(b) Other Means of Identification: Iron ore tailings, course tails, taconite aggregate, AM USA-1002 **1(c) Recommended Use of the Chemical and Restrictions on Use:** Blast furnace feed, no restrictions **1(d) Name, Address, and Telephone Number:**

ArcelorMittal USA LLC Phone number : 219-787-4901 **or email at:** msdssupport@arcelormittal.com
1 South Dearborn Street Chicago, IL 60603-9888

1(e) Emergency Phone Number: CHEMTREC (Day or Night) 1-800-424-9300

Section 2 – Hazard(s) Identification

2(a) Classification of the Chemical: Taconite Tailings is considered a hazardous material according to the criteria specified in REACH [REGULATION (EC) No 1907/2006] and CLP [REGULATION (EC) No 1272/2008] and OSHA 29 CFR 1910.1200 Hazard Communication Standard. The categories of Health Hazards as defined in "GLOBALLY HARMONIZED SYSTEM OF CLASSIFICATION AND LABELLING OF CHEMICALS (GHS), Third revised edition ST/SG/AC.10/30/Rev. 3" United Nations, New York and Geneva, 2009 have been evaluated. Refer to Section 3, 8 and 11 for additional information.

2(b) Signal Word, Hazard Statement(s), Symbols and Precautionary Statement(s):

Hazard Symbol	Hazard Classification	Signal Word	Hazard Statement(s)
	Carcinogenicity -1A Single Target Organ Toxicity (STOT) Single Exposure -2 STOT Repeated Exposure-1	**Danger**	May cause cancer. May cause mechanical irritation to skin and lung irritation. Causes damage to lungs. Causes skin irritation. Causes serious eye damage. Harmful if swallowed.
	Eye Irritation - 1		
	Acute Toxicity-Oral - 4 Skin Irritation - 2		

Precautionary Statement(s):

Prevention	Response	Storage/Disposal
Do not breathe dusts or fume. Wear protective gloves / eye protection / face protection. Wash thoroughly after handling. Obtain special instructions before use. Do not handle until all safety precautions have been read and understood. Do not eat, drink or smoke when using this product.	If exposed, concerned or feel unwell: Get medical advice/attention, call a poison center or doctor/physician. If in eyes: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing. Immediately call a poison center or doctor/physician. If on skin: Take off contaminated clothing and wash it before reuse. Wash with plenty of water. If skin irritation occurs: Get medical advice/attention. If swallowed: Call a poison center or doctor/physician if you feel unwell. Rinse mouth.	Dispose of contents in accordance with federal, state and local regulations. Store locked up.

2(c) Hazards Not Otherwise Classified: None Known
2(d) Unknown Acute Toxicity Statement (mixture): None Known

Section 3 – Composition/Information on Ingredients

3(a-c) Chemical Name, Common Name (Synonyms), CAS Number and Other Identifiers, and Concentration::

Chemical Name	CAS Number	EC Number	% weight
Crystalline Silica (as Quartz)	14808-60-7	238-878-4	> 50
Hematite	1317-60-8	215-275-4	5 – 15
Siderite	563-71-3	209-259-6	3 - 7
Magnetite	1309-38-2	215-169-8	2 - 4

Section 3 – Composition/Information on Ingredients (continued)

3(a-c) Chemical Name, Common Name (Synonyms), CAS Number and Other Identifiers, and Concentration:(continued)

Chemical Name	CAS Number	EC Number	% weight
Goethite	1310-14-1	214-176-6	2 – 4
Talc	14807-96-6	238-877-9	< 8

EC- European Community
CAS- Chemical Abstract Service

- **Taconite Tailings** contain small amounts of various elements in addition to those listed. These small quantities are frequently referred to as "trace" or "residual" elements. Taconite Tailings may contain the following trace or residual elements that are classified as nonhazardous: Ankerite (CAS # 3486-35-9: 3-6%), Stilpnomelane (3-6%), Apatite (<1%), Greenalite (<2%), Minnesotaite (1-5%).
- Percentages are expressed as typical ranges or maximum concentrations for the purpose of communicating the potential hazards of the finished product. Consult product specifications for specific composition information.

Section 4 – First-aid Measures

4(a) Description of Necessary Measures: If exposed, concerned or feel unwell: Get medical advice/attention, call a poison center or doctor/physician.

- **Inhalation:** If exposed, concerned or feel unwell: Get medical advice/attention, call a poison center or doctor/physician.
- **Eye Contact:** If in eyes: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing. Immediately call a poison center or doctor/physician.
- **Skin Contact:** If on skin: Take off contaminated clothing and wash it before reuse. Wash with plenty of water. If skin irritation occurs: Get medical advice/attention.
- **Ingestion:** If swallowed: Call a poison center or doctor/physician if you feel unwell. Rinse mouth.

4(b) Most Important Symptoms/Effects, Acute and Delayed (Chronic): Taconite Tailings, in its natural state, do not present an ingestion or contact hazard. Proper PPE should be worn, as required, where there is a concern of inhalation of quartz or silicon dust at levels over exposure limits, refer to Section 8. The product identified on this SDS is not a pure mineral but in a rock form which is an aggregate of minerals (or mixture). This product does not have the same properties that are found in a pure mineral or processed form. However, operations which reduce the particle to inhalable fractions by such methods as grinding, crushing, pulverizing or other similar processes; may result in the following effects if exposures exceed recommended limits as listed in Section8.

Acute Effects:

- **Inhalation:** Excessive exposure to high concentrations of dust may cause irritation to the eyes, skin and mucous membranes of the upper respiratory tract.
- **Eye:** Particles of iron or iron compounds may become imbedded in the eye. Excessive exposure to high concentrations of dust may cause irritation to the eyes.
- **Skin:** Skin contact with dusts may cause irritation or sensitization, possibly leading to dermatitis. Skin contact with metallic and dusts may cause physical abrasion.
- **Ingestion:** Ingestion of dust may cause nausea and/or vomiting.

Chronic Effects:

Individuals with chronic respiratory disorders (i.e., asthma, chronic bronchitis, emphysema, etc.) may be adversely affected by any fume or airborne particulate matter exposure. Persons with pre-existing skin disorders may be more susceptible to dermatitis.

Section 5 – Fire-fighting Measures

5(a) Suitable (and unsuitable) Extinguishing Media: Use extinguishers appropriate for surrounding materials.

5(b) Specific Hazards Arising from the Chemical: It is unlikely based on the chemistry of this material, in the metal oxide forms that it will present an explosion hazard. However, High concentrations of airborne metallic fines may present an explosion hazard.

5(c) Special Protective Equipment and Precautions for Fire-fighters: Self-contained NIOSH approved respiratory protection and full protective clothing should be worn when fumes and/or smoke from fire are present. Heat and flames cause emittance of acrid smoke and fumes. Do not release runoff from fire control methods to sewers or waterways. Firefighters should wear full face-piece self-contained breathing apparatus and chemical protective clothing with thermal protection. Direct water stream will scatter and spread flames and, therefore, should not be used.

Section 6 - Accidental Release Measures

6(a) Personal Precautions, Protective Equipment and Emergency Procedures: If material is in a dry state, avoid inhalation of dust. Personnel should be protected against contact with eyes and skin. Fine, dry material should be removed by vacuuming or wet sweeping methods to prevent spreading of dust. Avoid using compressed air. Collect material in appropriate, labeled containers for recovery or disposal in accordance with federal, state, and local regulations.

6(b) Methods and Materials for Containment and Clean Up: Collect material in appropriate, labeled containers for recovery or disposal in accordance with federal, state, and local regulations. Follow applicable OSHA regulations (29 CFR 1910.120) and all other pertinent state and federal requirements.

Section 7 - Handling and Storage

7(a) Precautions for Safe Handling: Do not eat, drink or smoke when using this product. Wash thoroughly after handling. Do not breathe dusts or fumes. Wear protective gloves / eye protection / face protection. Obtain special instructions before use. Do not handle until all safety precautions have been read and understood. Avoid direct contact on skin, eyes or on clothing. Emergency safety showers and eye wash stations should be present.

7(b) Conditions for Safe Storage, Including any Incompatibilities: Store away from acids and incompatible materials. Store locked up.

Section 8 - Exposure Controls / Personal Protection

8(a) Occupational Exposure Limits (OELs): The following exposure limits are offered as reference, for an experience industrial hygienist to review.

Ingredients	OSHA PEL [1]	ACGIH TLV [2]	NIOSH REL [3]	IDLH [4]
Crystalline Silica (as Quartz)	($30mg/m^3$)/(%SiO_2+2) (as total dust) ($10mg/m^3$)/(%SiO_2+2) (as respirable fraction)	0.025 mg/m^3	0.05 mg/m^3	50 mg/m^3
Iron Oxides (Hematite, Magnetite and Goethite)	10 mg/m^3 (as iron oxide fume)	5.0 mg/m^3	5.0 mg/m^3 (as iron oxide dust and fume)	2,500 mg/m^3
Siderite	15 mg/m^3 (as total dust, PNOR [5]) 5.0 mg/m^3 (as respirable fraction, PNOR)	10 mg/m^3 (as inhalable fraction [6], PNOS [7]) 3.0 mg/m^3 (as respirable fraction,[8] PNOS)	NE	NE
Talc	20 mppcf [9](containing less than 1% Quartz)	2.0 mg/m^3 (respirable fraction of the aerosol)	2.0 mg/m^3 (respirable)	1000 mg/m^3

NE - None Established

1. OSHA PELs (Permissible Exposure Limits) are 8-hour TWA (time-weighted average) concentrations unless otherwise noted. A ("C") designation denotes a ceiling limit, which should not be exceeded during any part of the working exposure unless otherwise noted. An Action level (AL) is used by OSHA and NIOSH to express a health or physical hazard. They indicate the level of a harmful or toxic substance/activity, which requires medical surveillance, increased industrial hygiene monitoring, or biological monitoring. Action Levels are generally set at one half of the PEL but the actual level may vary from standard to standard. The intent is to identify a level at which the vast majority of randomly sampled exposures will be below the PEL.
2. Threshold Limit Values (TLV) established by the American Conference of Governmental Industrial Hygienists (ACGIH) are 8-hour TWA concentrations unless otherwise noted. ACGIH TLVs are for guideline purposes only and as such are not legal, regulatory limits for compliance purposes. A Short Term Exposure Limit (STEL) is defined as the maximum concentration to which workers can be exposed for a short period of time (15 minutes) for only four times throughout the day with at least one hour between exposures.
3. The National Institute for Occupational Safety and Health Recommended Exposure Limits (NIOSH-REL) - Compendium of Policy and Statements. NIOSH, Cincinnati, OH (1992). NIOSH is the federal agency designated to conduct research relative to occupational safety and health. As is the case with ACGIH TLVs, NIOSH RELs are for guideline purposes only and as such are not legal, regulatory limits for compliance purposes.
4. The "Immediately Dangerous to Life or Health air concentration values (IDLHs)" are used by NIOSH as part of the respirator selection criteria and were first developed in the mid-1970's by NIOSH. The Documentation for Immediately Dangerous to Life or Health Concentrations (IDLHs) is a compilation of the rationale and sources of information used by NIOSH during the original determination of 387 IDLHs and their subsequent review and revision in 1994.
5. PNOR (Particulates Not Otherwise Regulated). All inert or nuisance dusts, whether mineral, inorganic, or organic, not listed specifically by substance name are covered by a limit which is the same as the inert or nuisance dust limit of 15 mg/m^3 for total dust and 5 mg/m^3 for the respirable fraction.
6. Inhalable fraction. The concentration of inhalable particulate for the application of this TLV is to be determined from the fraction passing a size-selector with the characteristics defined in the ACGIH 2013 TLVs ® and BEIs ® (Biological Exposure Indices) Appendix D, paragraph A.
7. PNOS (Particulates Not Otherwise Specified). Particulates identified under the PNOS heading are "nuisance dusts" containing no asbestos and <1% crystalline silica.
8. Respirable fraction. The concentration of respirable dust for the application of this limit is to be determined from the fraction passing a size-selector with the characteristics defined in ACGIH 2013 TLVs ® and BEIs ® Appendix D, paragraph C.
9. Million particles per cubic feet

8(b) Appropriate Engineering Controls: Local exhaust ventilation should be used to control the emission of air contaminants. General dilution ventilation may assist with the reduction of air contaminant concentrations. Emergency eye wash stations and deluge safety showers should be available in the work area.

8(c) Individual Protection Measures:

- **Respiratory Protection:** Seek professional advice prior to respirator selection and use. Follow OSHA respirator regulations (29 CFR 1910.134) and, if necessary, use only a NIOSH-approved respirator. Select respirator based on its suitability to provide adequate worker protection for given working conditions, level of airborne contamination, and presence of sufficient oxygen. Concentration in air of the various contaminants determines the extent of respiratory protection needed. Half-face, negative-pressure, air-purifying respirator equipped with P100 filter is acceptable for concentrations up to 10 times the exposure limit. Full-face, negative-pressure, air-purifying respirator equipped with P100 filter is acceptable for concentrations up to 50 times the exposure limit. Protection by air-purifying negative- pressure and powered air respirators is limited. Use a positive-pressure-demand, full-face, supplied air respirator or self contained breathing apparatus (SCBA) for concentrations above 50 times the exposure limit. If exposure is above the IDLH (Immediately dangerous to life or health) for any of the constituents, or there is a possibility of an uncontrolled release or exposure levels are unknown, then use a positive- demand, full-face, supplied air respirator with escape bottle or SCBA.

Warning! Air-purifying respirators both negative-pressure, and powered-air do not protect workers in oxygen-deficient atmospheres.

- **Eyes**: Wear appropriate eye protection to prevent eye contact. Use safety glasses with side shields or chemical goggles.

- **Skin**: Persons handling this product should wear protective gloves.
- **Other Protective Equipment**: An eyewash fountain and deluge shower should be readily available in the work area.

Section 9 - Physical and Chemical Properties

9(a) Appearance (physical state, color, etc.): Solid. Reddish - brown grayish, small pebbles
9(b) Odor: No Odor
9(c) Odor Threshold: NA
9(d) pH: NA
9 (e) Melting Point/Freezing Point: >2,800° F (>1537°C)
9(f) Initial Boiling Point and Boiling Range: NA
9(g) Flash Point: NA
9(h) Evaporation Rate: NA
9(i) Flammability (solid, gas): Non-flammable, non-combustible
9(j) Upper/lower Flammability or Explosive Limits: NA to
9(k) Vapor Pressure: NA
9(l) Vapor Density (Air = 1): NA
9(m) Relative Density: 2.7 -3.2 (SG)
9(n) Solubility(ies): Insoluble
9(o) Partition Coefficient n-octanol/water: NA
9(p) Auto-ignition Temperature: ND
9(q) Decomposition Temperature: ND
9(r) Viscosity: ND

NA - Not Applicable
ND - Not Determined for product as a whole

Section 10 - Stability and Reactivity

10(a) Reactivity: Not Determined (ND)
10(b) Chemical Stability: Taconite Tailings is stable under normal storage and handling conditions.
10(c) Possibility of Hazardous Reaction: None Known
10(d) Conditions to Avoid: Storage with strong acids or calcium hypochlorite.
10(e) Incompatible Materials: Will react with strong acids to form hydrogen. Iron oxide dusts in contact with calcium hypochlorite evolve oxygen and may cause an explosion.
10(f) Hazardous Decomposition Products: Toxic fumes and vapors may be released at elevated temperatures.

Section 11 - Toxicological Information

11 Information on Toxicological Effects: The following toxicity data has been determined for **Taconite Tailings** by using the information available for its components applied to the guidance on the preparation of an SDS under the GHS requirements of OSHA and the EU CPL:

Hazard Classification	Hazard Category		Hazard Symbols	Signal Word	Hazard Statement
	EU	OSHA			
Acute Toxicity Hazard (covers Categories 1-4)	4	4[a]		**Warning**	Harmful if swallowed.
Skin Irritation (covers Categories 1A, 1B, and 2)	2	2[b]		**Warning**	Causes skin irritation.
Eye Damage/Irritation (covers Categories 1, 2A and 2B)	1	1[c]		**Danger**	Causes serious eye damage.
Germ Cell Mutagenicity (covers Categories 1A, 1B and 2)	2	NR*	NA	**NA**	NA
Carcinogenicity (covers Categories 1A, 1B and 2)	1A	1A[g]		**Danger**	May cause cancer.
Specific Target Organ Toxicity (STOT) Following Single Exposure (covers Categories 1-3)	2	2[i]		**Warning**	May cause mechanical irritation to skin and lung irritation.
STOT Following Repeated Exposure (covers Categories 1 and 2)	1	1[j]		**Danger**	Causes damage to lungs.

* NR Not Rated - Available data does not meet criteria for classification.

The Toxicological data listed below are presented regardless to classification criteria. Individual hazard classification categories where the toxicological information has met or exceeded a classification criteria threshold are listed above.

a. No LC_{50} or LD_{50} has been established for **Taconite Tailings**. The following data has been determined for the components:
   - **Silica:** LD_{50} = 500 mg/kg (Oral/ Rat)
   - **Iron Oxide:** LD_{50}= >10,000 mg/kg (Oral/ Rat)

b. No Skin (Dermal) Irritation data available for **Taconite Tailings** as a mixture. The following Skin (Dermal) Irritation data has been determined for the components:
   - **Iron Oxide:** Moderately irritating

Section 11 - Toxicological Information (continued)

11 Information on Toxicological Effects (continued):

c. No Eye Irritation data available for **Taconite Tailings** as a mixture. The following Eye Irritation information was found for the components:
- **Silicon Dioxide:** Crystalline silica may cause abrasion of the cornea**.**
- **Iron Oxide:** Severely irritating; may cause burns. Human Corrosive (IUCLID).

d. No Skin (Dermal)/Respiratory Sensitization data available for **Taconite Tailings** as a mixture or its individual components.

e. No Aspiration Hazard data available for **Taconite Tailings** as a mixture or its individual components.

f. No Germ Cell Mutagenicity data available for **Taconite Tailings** as a mixture. The following Germ Cell Mutagenicity information was found for the components:
- **Iron Oxide:** Both positive and negative data.

g. Carcinogenicity: IARC, NTP, and OSHA do not list **Taconite Tailings** as carcinogens. The following Carcinogenicity information was found for the components:
- **Silicon Dioxide:** Repeated exposure to crystalline silica causes lung cancer in exposed humans. IARC-1, NTP-1, TLV-A2, and OSHA.
- **Iron Oxide:** IARC-3, TLV-A4.
- **Talc**: Talc not containing Asbestos is IARC rated as Group 3 (not classifiable as to its carcinogenicity to humans).

h. No Toxic Reproduction data available for **Taconite Tailings** as a mixture or its individual components.

i. No Specific Target Organ Toxicity (STOT) following a Single Exposure data available for **Taconite Tailings** as a mixture. The following STOT following a Single Exposure data was found for the components:
- **Silicon Dioxide:** Single exposure to very high airborne levels may cause lung irritation in exposed humans.
- **Iron Oxide:** May cause lung irritation.

j. No Specific Target Organ Toxicity (STOT) following Repeated Exposure data was available **for Taconite Tailings** as a whole. The following STOT following Repeated Exposure data was found for the components:
- **Silicon Dioxide:** Repeated exposure to crystalline silica causes silicosis and kidney damage as well as increased incidence of autoimmune disorders in humans.
- **Iron Oxide:** Some pulmonary and lung effects reported.

The above toxicity information was determined from available scientific sources to illustrate the prevailing posture of the scientific community. The scientific resources includes: The American Conference of Governmental Industrial Hygienist (ACGIH) Documentation of the Threshold Limit Values (TLVs) and Biological Exposure indices (BEIs) with Other Worldwide Occupational Exposure Values 2009, The International Agency for Research on Cancer (IARC), The National Toxicology Program (NTP) updated documentation, the World Health Organization (WHO) and other available resources, the International Uniform Chemical Information Database (IUCLID), European Union Risk Assessment Report (EU-RAR), Concise

The following health hazard information is provided regardless to classification criteria and is based on the individual component(s):

Acute Effects by Component:
- **CRYSTALINE SILICA (Silicon Dioxide):** Causes irritation and inflammation of the respiratory tract. May cause abrasion of the cornea. Inhalation may cause cough. A single exposure to very high airborne levels may cause lung irritation in exposed humans.
- **IRON OXIDE:** Contact with iron oxide has been reported to cause skin irritation and serious eye damage.
- **SIDERITE:** Not Rated/Not Classified
- **TALC:** Not Rated/Not Classified

Delayed (chronic) Effects by Component:
- **SILICA (Crystalline Quartz):** Inhalation of quartz is classified by IARC as a probable human carcinogen. Chronic exposure can cause silicosis, a form of lung scarring that can cause shortness of breath, reduced lung function, and in severe cases, death. Repeated exposure may cause kidney damage as well as increased incidence of autoimmune disorder.
- **IRON OXIDE:** Chronic inhalation of excessive concentrations of iron oxide fumes or dusts may result in the development of a benign lung disease, called siderosis, which is observable as an X-ray change. No physical impairment of lung function has been associated with siderosis. Inhalation of excessive concentrations of ferric oxide may enhance the risk of lung cancer development in workers exposed to pulmonary carcinogens. Iron oxide is listed as a Group 3 (not classifiable) carcinogen by the International Agency for Research on Cancer (IARC).
- **SIDERITE:** Not Rated/Not Classified

Section 12 - Ecological Information

12(a) Ecotoxicity (aquatic & terrestrial): No data available for the product, **Taconite Tailings** as a whole. However, individual components of the product have been found to be toxic to the environment. Dusts may migrate into soil and groundwater and be ingested by wildlife as follows:

- **Iron Oxide**: LC_{50}: >1000 mg/L; Fish

12(b) Persistence & Degradability: No Data Available

12(c) Bioaccumulative Potential: No Data Available **12(d)**

Mobility (in soil): No Data Available

12(e) Other Adverse Effects: None Known

Additional Information:

Hazard Category: No Category

Signal Word: No Signal Word

Hazard Symbol: No Hazard Symbol

Hazard Statement: No Hazard Statement

Section 13 - Disposal Considerations

Disposal: This material can be disposed of as an inert solid in a landfill or by other procedures which are in accordance with local, state, and Federal regulations. This material may also be reclaimed for reuse.

Container Cleaning and Disposal: Follow applicable federal, state and local regulations. Observe safe handling precautions.

Please note this information is for Taconite Tailings in its original form. Any alterations can void this information.

Section 14 - Transport Information

14 (a-g) Transportation Information:

US Department of Transportation (DOT) under 49 CFR 172.101 does not regulate **Taconite Tailings** as a hazardous material. All federal, state, and local laws and regulations that apply to the transport of this type of material must be adhered to.

Shipping Name: Not Applicable (NA) **Shipping Symbols:** NA **Hazard Class:** NA **UN No.:** NA **Packing Group** NA **DOT/ IMO Label:** NA **Special Provisions (172.102):** NA	**Packaging Authorizations** a) **Exceptions:** NA b) **Non-bulk:** NA c) **Bulk:** NA	**Quantity Limitations** a) **Passenger Aircraft or Rail:** NA b) **Cargo Aircraft Only:** NA **Vessel Stowage Location:** NA

International Maritime Dangerous Goods (IMDG) and the Regulations Concerning the International Carriage of Dangerous Goods by Rail (RID) classification, packaging and shipping requirements follow the US DOT Hazardous Materials Regulation.

Regulations Concerning the International Carriage of Dangerous Goods by Road (ADR) does not regulate **Taconite Tailings** as a hazardous material.

Shipping Name: Not Applicable (NA) **Classification Code:** NA **UN No.:** NA **Packing Group:** NA **ADR Label:** NA **Special Provisions:** NA **Limited Quantities:** NA	**Packaging** a) **Packing Instructions:** NA b) **Special Packing Provisions:** NA c) **Mixed Packing Provisions:** NA	**Portable Tanks & Bulk Containers** a) **Instructions:** NA b) **Special Provisions:** NA

International Air Transport Association (IATA) does not regulate **Taconite Tailings** as a hazardous material.

	Passenger & Cargo Aircraft	Limited Quantity (EQ)	Cargo Aircraft Only	Special Provisions:
Shipping Name: Not Applicable (NA) **Class/Division:** NA **Hazard Label (s):** NA **UN No.:** NA **Packing Group:** NA **Excepted Quantities (EQ):** NA	**Pkg Inst:** NA **Max Net Qty/Pkg:**	**Pkg Inst:** NA **Max Net Qty/Pkg:**	**Pkg Inst:** NA **Max Net Qty/Pkg:** NA	NA **ERG Code:** NA

Pkg Inst – Packing Instructions Max Net Qty/Pkg – Maximum Net Quantity per Package ERG – Emergency Response Drill Code

Taconite Tailings does not have a **Transport Dangerous Goods (TDG)** classification.

Section 15 - Regulatory Information

Regulatory Information: *The following listing of regulations relating to an ArcelorMittal product may not be complete and should not be solely relied upon for all regulatory compliance responsibilities.* This product and/or its constituents are subject to the following regulations:

OSHA Regulations: Air Contaminant (29 CFR 1910.1000, Table Z-1, Z-2, Z-3): The product as a whole is not listed. However, individual components of the product are listed refer to Section 8.

EPA Regulations: The product, **Taconite Tailings** is not listed as a whole. However, individual components of the product are listed:

Components	Regulations
Manganese	CERCLA
CAS #	Chemical Name
7439-96-5	Manganese

SARA Potential Hazard Categories: Immediate Acute Health Hazard; Delayed Chronic Health Hazard

Section 313 Supplier Notification: The product, **Taconite Tailings** contains the following toxic chemicals subject to the reporting requirements of section 313 of the Emergency Planning and Community Right-to-Know Act and 40 CFR part 372:

Please also note that if you prepackage or otherwise redistribute this product to industrial customers, SARA 313 requires that a notice be sent to those customers.

Section 15 - Regulatory Information (continued)

EPA Regulations (continued):

Regulations Key:

CAA	Clean Air Act (42 USC Sec. 7412; 40 CFR Part 61 [As of: 8/18/06])
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act (42 USC Secs. 9601(14), 9603(a); 40 CFR Sec. 302.4, Table 302.4, Table 302.4 and App. A)
CWA	Clean Water Act (33 USC Secs. 1311; 1314(b), (c), (e), (g); 136(b), (c); 137(b), (c) [as of 8/2/06])
RCRA	Resource Conservation Recovery Act (42 USC Sec. 6921; 40 CFR Part 261 App VIII)
SARA	Superfund Amendments and Reauthorization Act of 1986 Title III Section 302 Extremely Hazardous Substances (42 USC Secs. 11023, 13106; 40 CFR Sec. 372.65) and Section 313 Toxic Chemicals (42 USC Secs. 11023, 13106; 40 CFR Sec. 372.65 [as of 6/30/05])
TSCA	Toxic Substance Control Act (15 U.S.C. s/s 2601 et seq. [1976])

State Regulations: The product, **Taconite Tailings** as a whole is not listed in any state regulations. However, individual components of the product are listed in various state regulations:

Pennsylvania Right to Know: Contains regulated material in the following categories:

- Hazardous Substances: Silica (quartz) and Talc
- Special Hazard Substances: Silica(quartz)

California Prop. 65: Contains elements known to the State of California to cause cancer or reproductive toxicity. This includes Crystalline silica (airborne particles of respirable size only).

New Jersey: Contains regulated material in the following categories:

- Hazardous Substance: Talc and Crystalline silica
- Special Health Hazard Substances: Talc and Crystalline silica

Minnesota: Crystalline silica (inhaled in the form of quartz or cristobalite from occupational source).

Massachusetts: Crystalline silica

Other Regulations:

WHMIS Classification (Canadian): The product, **Taconite Tailings** is not listed as a whole. However individual components are listed.

Ingredients		WHMIS Classification
Quartz		D-2A

This product has been classified in accordance with the hazard criteria of the Controlled Products Regulations and the SDS contains all the information required by the Controlled Products Regulations.

Section 16 - Other Information

Prepared By: ArcelorMittal

Revision History:

5/22/2009 - Original Issue Date

8/20/2014 - Update to OSHA HAZ COM 2012

Additional Information:

Hazardous Material Identification System (HMIS) Classification

Health Hazard	1
Fire Hazard	0
Physical Hazard	0

HEALTH= **1**, * Denotes possible chronic hazard if airborne dusts or fumes are generated

HEALTH = **1**, Exposure could cause irritation but only minor residual injury even if no Irritation or minor reversible injury possible treatment is given.

FIRE= **0**, Materials that will not burn.

PHYSICAL HAZARDS = **0**, Materials that are normally stable, even under fire conditions, and will not react with water, polymerize, decompose, condense, or self-react. Non-explosives.

National Fire Protection Association (NFPA)

FIRE = **0,** Materials that will not burn.

INSTABILITY = **0**, Normally stable, even under fire exposure conditions, and are not reactive with water.

ABBREVIATIONS/ACRONYMS:

ACGIH	American Conference of Governmental Industrial Hygienists		**NIF**	No Information Found
BEIs	Biological Exposure Indices		**NIOSH**	National Institute for Occupational Safety and Health
CAS	Chemical Abstracts Service		**NTP**	National Toxicology Program
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act		**ORC**	Organization Resources Counselors
CFR	Code of Federal Regulations		**OSHA**	Occupational Safety and Health Administration
CNS	Central Nervous System		**PEL**	Permissible Exposure Limit
GI, GIT	Gastro-Intestinal, Gastro-Intestinal Tract		**PNOR**	Particulate Not Otherwise Regulated
HMIS	Hazardous Materials Identification System		**PNOC**	Particulate Not Otherwise Classified
IARC	International Agency for Research on Cancer		**PPE**	Personal Protective Equipment
LC50	Median Lethal Concentration		**ppm**	parts per million
LD50	Median Lethal Dose		**RCRA**	Resource Conservation and Recovery Act

Section 16 - Other Information (continued)

ABBREVIATIONS/ACRONYMS (continued):

LD_{Lo}	Lowest Dose to have killed animals or humans	**RTECS**	Registry of Toxic Effects of Chemical Substances
LEL	Lower Explosive Limit	**SARA**	Superfund Amendment and Reauthorization Act
$\mu g/m^3$	microgram per cubic meter of air	**SCBA**	Self-contained Breathing Apparatus
mg/m^3	milligram per cubic meter of air	**STEL**	Short-term Exposure Limit
mppcf	million particles per cubic foot	**TLV**	Threshold Limit Value
SDS	Safety Data Sheet	**TWA**	Time-weighted Average
MSHA	Mine Safety and Health Administration	**UEL**	Upper Explosive Limit
NFPA	National Fire Protection Association		

Disclaimer: This information is taken from sources or based upon data believed to be reliable. Our objective in sending this information is to help you protect the health and safety of your personnel and to comply with the OSHA Hazard Communication Standard and Title III of the Superfund Amendment and Reauthorization Act of 1986. ArcelorMittal USA LLC makes no warranty as to the absolute correctness, completeness, or sufficiency of any of the foregoing, or any additional, or other measures that may not be required under particular conditions. ARCELORMITTAL USA LLC MAKES NO WARRANTIES, EXPRESS OR IMPLIED, INCLUDING THE IMPLIED WARRANTY OF MERCHANTABILITY, OR ANY IMPLIED WARRANTY OF FITNESS FOR A PARTICULAR PURPOSE, AND ANY IMPLIED WARRANTIES OTHERWISE ARISING FROM COURSE OF DEALING OR TRADE.

Taconite Tailings

Signal Word: **DANGER**

Symbols:

HAZARD STATEMENTS:

May cause cancer.
May cause mechanical irritation to skin and lung irritation.
Causes damage to lungs. Causes skin irritation.
Causes serious eye damage.
Harmful if swallowed.

PRECAUTIONARY STATEMENTS:

Do not breathe dusts or fume.
Wear protective gloves / eye protection / face protection.
Wash thoroughly after handling.
Obtain special instructions before use.
Do not handle until all safety precautions have been read and understood.
Do not eat, drink or smoke when using this product.
If exposed, concerned or feel unwell: Get medical advice/attention, call a poison center or doctor/physician.
If in eyes: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing.
Immediately call a poison center or doctor/physician.
If on skin: Take off contaminated clothing and wash it before reuse. Wash with plenty of water. If skin irritation occurs: Get medical advice/attention.
If swallowed: Call a poison center or doctor/physician if you feel unwell. Rinse mouth.
Dispose of contents in accordance with federal, state and local regulations.
Store locked up.

SDS ID No.: AM USA-1002

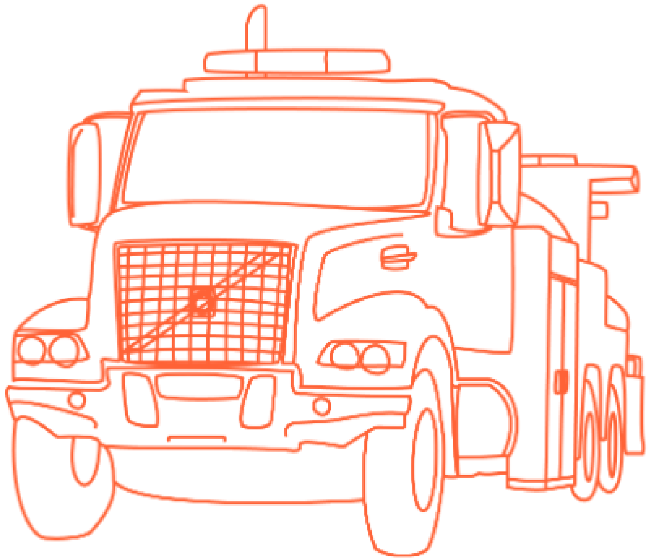
ArcelorMittal USA LLC 1 South Dearborn Street Chicago, IL 60603-9888

General Information: Phone: 219-787-4901 or email at: msdssupport@arcelormittal.com
CHEMTREC (Day or Night): 1-800-424-9300
Emergency Contact: 1-760-476-3962, (3E Company Code: 333211)
Original Issue Date: 05/22/2009 **Revised:** 08/20/2014

Appendix F: St. Louis County, CSAH 15, Munger Shaw Road Scrim Data Review - Isaac Briskin, WDM USA

St. Louis County, CSAH 15, Munger Shaw Road SCRIM Data Review

September 4th, 2024



We Deliver More

OUTLINE

1. Data Overview
2. Friction and SCRIM Reading Context
3. Friction and Macrotexture Results
4. Contact Information

We Deliver More

Data Overview

Our project's surface treated test sections (1 to 5) were installed in the northbound lane of CSAH 15 in 2021. Section 0 is the untreated control.

In 2020, calcined bauxite was installed by St. Louis County on the horizontal curve just to the south.

We Deliver More

Data Overview

- 3 repeated SCRIM Surveys
- Surveying 5 test sections and 4 control or gap pavements
- Data is in long format i.e. all Run 1 data precedes Run 2 data, instead of being aligned side-by-side

Column Name	Description
Testrun	Survey and Run label, with datetime stamp
Run	Run number, 1-3
Distance	Distance from start of survey in feet
Speed_mph	Survey Speed in mph
Section	Section, as defined by pavement
SpeedCorrectedSR	Speed corrected (to 40 mph) SCRIM Reading
MPD	Mean Profile Depth, a macrotexture measure
IRI	International Roughness Index, IRI
Gradient	Gradient, a measure of slope
Cross Slope	Cross Sectional Slope
Curve Radius	Curve radius in feet
Latitude	Latitude coordinate
Longitude	Longitude coordinate

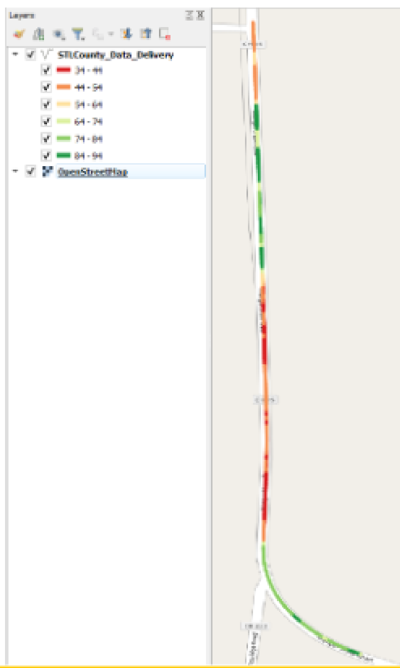
testrun	Run	Distance	Speed_mph	Section	SpeedCorrectedSR	MPD	IRI	Gradient	CrossSlope	CurveRadius	Latitude	Longitude
Mn_STloCO_40_SM08_240726121911	Run 1	211.2	34	-1. Calcined Bauxite 2020	67	1.375	207	-0.34	5.04	203	46.912614	-92.342578
Mn_STloCO_40_SM08_240726121911	Run 1	237.6	35	-1. Calcined Bauxite 2020	86.9	1.21	41	0.12	5.64	919	46.912647	-92.342672
Mn_STloCO_40_SM08_240726121911	Run 1	264	35	-1. Calcined Bauxite 2020	83.2	1.14	74	0.33	5.96	692	46.912682	-92.342765
Mn_STloCO_40_SM08_240726121911	Run 1	290.4	37	-1. Calcined Bauxite 2020	77.8	1.09	88	0.52	6.23	581	46.912719	-92.342855
Mn_STloCO_40_SM08_240726121911	Run 1	316.8	37	-1. Calcined Bauxite 2020	78	1.07	46	0.77	6.2	788	46.912759	-92.342943
Mn_STloCO_40_SM08_240726121911	Run 1	343.2	38	-1. Calcined Bauxite 2020	80	1.09	44	0.89	6.13	965	46.912801	-92.343029
Mn_STloCO_40_SM08_240726121911	Run 1	369.6	38	-1. Calcined Bauxite 2020	77.3	1.03	99	0.9	6.04	680	46.912845	-92.343114
Mn_STloCO_40_SM08_240726121911	Run 1	396	38	-1. Calcined Bauxite 2020	73.1	0.896	62	0.94	6.13	909	46.912891	-92.343196
Mn_STloCO_40_SM08_240726121911	Run 1	422.4	38	-1. Calcined Bauxite 2020	81.2	1.12	44	1.13	6.4	712	46.912938	-92.343275
Mn_STloCO_40_SM08_240726121911	Run 1	448.8	38	-1. Calcined Bauxite 2020	79.3	1.18	41	1.41	6.7	613	46.912988	-92.343353

Friction and SCRIM Reading Context

- Friction, measured by SCRIM Reading (SR), corrected to 40 mph, follows the distribution
  - Range: 10 – 120
  - Poor Friction: < 45
  - Investigatory Level/Minimum Sufficient Friction: >56
  - Great Friction: > 67
  - HFST Friction Range: 75 – 105

Friction and Macrotexture Results

The SCRIM picks up changes in friction that delineate changes in pavements on Munger Shaw Rd



Friction and Macrotexture Results

1. The SCRIM picks up changes in friction and macrotexture that delineate changes in pavements in all 3 runs
2. GSB -6 Taconite has the lowest friction & macrotexture, followed by the existing control and GSB -8 Taconite
3. Both HFST Taconite/Bauxite have high friction, with SR values resembling HFST in other states
4. The control/existing pavement had the highest macrotexture

	SR				MPD		
Section	Run 1	Run 2	Run 3		Run 1	Run 2	Run 3
-1. Calcined Bauxite 2020	79.5	77.5	80		1.19	1.19	1.18
0. Existing Pavement	44	42.4	43.2		1.72	1.76	1.69
1. GSB -8 Taconite	46.9	46.2	46.7		0.85	0.85	0.87
2. GSB -6 Taconite	42.5	40.2	43.9		0.58	0.58	0.62
2.5. Gap 100'	62.5	61.6	62.6		1.03	1.05	1.07
3. HFST Taconite	85.3	83.6	84.2		0.91	0.9	0.95
3.5. Gap 35'	70.8	71.9	69.9		0.99	1	1.02
4. HFST Bauxite	85.9	83.8	84.6		0.98	1.02	1.01
5. New GSB -8 Taconite	51.5	51.4	50.9		0.69	0.72	0.65

Friction and Macrotexture Results

1. The table below shows the averages over 3 runs for each pavement section
2. The HFST Taconite and Bauxite SR values have both the highest friction/SR, as well as the highest standard deviation within the sections, with values ranging from 68 to 94, with the 2/3 (67%) of the data sitting between 82 and 89.

Section	Survey Length (Feet)	Mean SR	SD SR	Mean MPD	SD MPD
-1. Calcined Bauxite 2020	871.2	79	3.7	1.18	0.11
0. Existing Pavement	475.2	43.2	1.7	1.72	0.1
1. GSB -8 Taconite	528	46.6	2.4	0.86	0.24
2. GSB -6 Taconite	554.4	42.2	3.8	0.59	0.08
2.5. Gap 100'	105.6	62.2	3.9	1.05	0.1
3. HFST Taconite	475.2	84.4	4.1	0.92	0.06
3.5. Gap 35'	52.8	70.9	2.1	1	0.03
4. HFST Bauxite	475.2	84.8	8.2	1	0.19
5. New GSB -8 Taconite	501.6	51.3	2.9	0.69	0.08

Questions or Feedback

If you have any questions about the data, or any future analyses:

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Appendix G: Comparative Preliminary Life Cycle Assessment (LCA) of Calcined Bauxite- and Taconite Tailings-based High Friction Surface Treatments (HFST) - Matthew Aro, NRRI

The technical report is available through the University of Minnesota Duluth, NRRI-TR-2023-01.pdf (470.52 KB)