Adequate Friction for the Road Ahead - Evaluation of Asphalt Mixture Friction Using Accelerated Laboratory Polishing

Phil Blankenship, MSCE, PE
President
Blankenship Asphalt Tech & Training, PLLC
Richmond, Kentucky
phil@blankenshipasphalttech.com

Stephen Goodman, Ph.D., P.Eng.
President
Goodman Pavement and Materials Engineering Inc.
Ottawa, Ontario
stephen@goodgrip.ca

Paper prepared for the session "The Road Ahead: Analyzing Futuristic Vehicle Technologies and Changing Traffic Impact on Pavement Life"
2026 Transportation Association of Canada (TAC) Conference & Exhibition
Winnipeg, Manitoba

Abstract

Regulations concerning the operation of Autonomous Vehicles (AVs) and Connected Autonomous Vehicles (CAVs) are evolving in North America. From a pavement perspective, these technologies will focus and intensify the applied loading with significant consequences to the structural and functional performance of our pavements. While maintaining adequate friction between the tire and pavement surface is critical to the safe operation of all vehicles, greater polishing effort from AVs and CAVs may accelerate friction loss. Unfortunately, historic approaches to approve polish-resistant aggregates or mixes may no longer be feasible to accurately or rapidly evaluate polish resistance for "the road ahead."

To accelerate the process, the NCAT Three-Wheel Polishing Device (TWPD) and Dynamic Friction Tester (DFT) offer a promising laboratory approach. Hot Mix Asphalt (HMA) produced with two aggregate sources in Kentucky was evaluated using the new AASHTO R 134 procedure including 150,000 polishing cycles. Extended polishing to 1,000,000 cycles was imparted as an exercise and yielded novel insights.

While routine TWPD polishing to 1 million cycles is not recommended due to excessive time and machine wear, the results did suggest that long-term polishing performance of aggregates is complex. Overall, the use of the TWPD and DFT presents a promising approach for the accelerated evaluation of HMA mixtures and new aggregate sources, with the goal of better managing pavement friction and saving lives on North American roadways.

Introduction

Impacts of Autonomous, Connected, and Electric Vehicles on Pavements

Regulations concerning the operation of Autonomous Vehicles (AVs) and Connected Autonomous Vehicles (CAVs) are evolving in North America. In Canada, the regulation of vehicles, particularly AVs, faces several unique legal challenges and distinctions due in large part to the country's federalist structure and the inherent complications a multi-layered government framework can create[1]. Regardless of the complexities, AVs will likely become commonplace by the end of this decade. From a pavement perspective, the increase in AVs and CAVs poses the following challenges[2]:

- Increased Highway Capacity: The automatic braking configured in the AV system will increase highway capacity along with other advantages including increased vehicle speed and reduced traffic congestion. Future pavements must therefore be designed to accommodate additional truck and passenger vehicle traffic from both structural (i.e. stability & durability) and functional (i.e. skid resistance and smoothness) perspectives.

- Reduced Lateral Wheel Wander: Existing pavement structural design methods have been calibrated to loadings applied by trucks driven by humans, who naturally allow the vehicle to wander laterally within the lane (Figure 1). The amount of wander depends upon the lane width, vehicle width and speed but typically follows an approximate normal distribution about the centreline[3]. The sophisticated sensor systems within AVs and CAVs will reduce the width of wander within a lane during operation. This has the benefit of improved roadway safety, however, will result in reduced pavement performance by channelizing wheel loads.

- Platooning of Truck Traffic: Connection of multiple heavy trucks will result in reduced inter-vehicle distance and therefore the time between axle loadings. HMA is a visco-elastic material whose response and recovery characteristics are influenced by loading frequency. Increased frequency may reduce pavement life by reducing the available recovery time between loads.

Primarily due to the mass of the batteries, Electric Vehicles (EVs) are heavier than vehicles powered by gasoline or diesel fuel – typically 10 to 15 percent for common passenger vehicles[4]. Collectively, the new operating conditions imposed by AV, CAV, and EV technology will influence surface characteristics such as polishing and skid resistance, which are the focus of this paper.

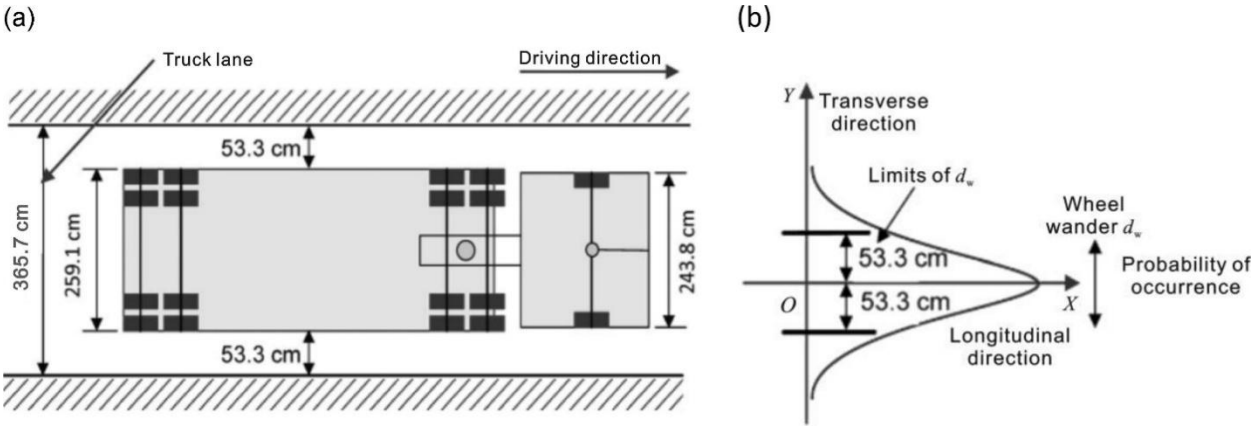


Figure 1. Distribution of Lateral Wander of Non-Autonomous Vehicle[5]

Surface Characteristics and Traffic Safety

In Canada, the number of annual fatalities has steadily reduced from 2,921 in 2002 to 1,964 in 2023[6]. Still, nearly 2,000 people die annually on Canadian roads - an unacceptable value. In the United States, roadway safety remains a major concern. According to NHTSA and the American Society of Civil Engineers (ASCE), an estimated 40,990 people were killed in motor vehicle crashes in 2023—about 112 fatalities each day[7]. Put another way, the annual death toll is comparable to several fully occupied commercial aircraft crashes every week.

Pavement surface characteristics including friction, texture, cracking and rutting are key factors associated with road infrastructure contributing to collisions. Indeed, the FHWA has identified Pavement Friction Management (PFM)[8] as a readily implementable countermeasure to reduce accidents and fatalities. PFM is a proactive approach to measure, monitor, and maintain pavement friction at appropriate levels throughout the pavement life cycle. It involves selecting suitable materials and designs, applying surface treatments, conducting regular inspections and tests, and implementing corrective actions when needed. PFM can enhance road safety by improving the performance and durability of the pavement surface and reducing the occurrence and severity of crashes.

Until recently, North American road agencies had not publicly identified or acknowledged acceptable pavement friction values. Some of this reticence resulted from the complexities inherent with the tire-pavement interface and friction and lack of data, but most has resulted from a fear of repercussion (i.e. litigation, budgetary, etc.). In February 2023, the FHWA released report FHWA SA-23-006[9] entitled "Characterizing Road Safety Performance Using Pavement Friction" that will prove to be a major catalyst in the widespread adoption of PFM by providing such values, referred to as "investigatory thresholds," for roadway agencies to reference and assist with their PFM programs.

The case for implementing a PFM program is compelling. Even nominal increases in network friction can result in a reduction in crash frequency of 10 percent[8] while the installation of High Friction Surface Treatments (HFSTs) at critical locations such as ramps can reduce crash frequency by over 60 percent[10]. A comprehensive Benefit-Cost analysis by the Pennsylvania Department of Transportation reported a mean Benefit-Cost Ratio (BCR) of 6.9 resulting from accident reduction at 122 HFST projects[11] while a multi-state evaluation of HFST sites found a BCR of 14.6[12]. An analysis of 17 tight curves in Florida over 5-years reported BCR values ranging between zero and 118 with an average of 24.5 for total crashes[13]. It is clear that a mature PFM program not only reduces accidents and saves lives but provides real return on investment.

Testing and Specifying Polish-Resistant Mixes & Aggregates

While HFST has been shown to provide excellent performance and (potentially) high BCR, it is important to note that the materials and installation equipment required are not available in all jurisdictions. Specifically, although the calcined bauxite aggregates used in HFST provide excellent performance, there are no sources in North America. Furthermore, HFST is not a universally applicable solution for reduced friction and not always the most cost-effective treatment selection[14].

Fortunately, good frictional performance can be achieved with traditional Hot Mix Asphalt (HMA) and other bituminous surface treatments such as chip seals and micro-surfacing incorporating naturally occurring aggregates. The key is to design mixtures that provide and maintain good macro-texture to promote hysteresis and prevent hydroplaning, and good micro-texture to enhance adhesion over the

life of the pavement surface. Macro-texture is primarily determined by the Nominal Maximum Aggregate Size (NMAS) and the gradation of the aggregates in the HMA or surface treatment[15]. Micro-texture is primarily related to the aggregate source(s) with different aggregate types such as limestone, dolomite, quartzite, gravel, etc. having different hardness, abrasion resistance, and polishing behaviour. Angular (i.e. crushed) aggregates also tend to provide higher friction than rounded aggregates[15]. Until recently however, no laboratory testing approach for the evaluation of long-term performance of friction and polish-resistance of compacted HMA was available. As a surrogate, many road agencies have developed specifications for assessing aggregate quality and polish-resistance in the laboratory, followed by field verification of HMA performance over time.

For example, agencies such as the Ontario Ministry of Transportation (MTO) and the Kentucky Transportation Cabinet (KYTC) have historically identified sources of polish-resistant aggregates through a multi-step process. First, the aggregates are subjected to a series of laboratory tests to determine chemical and mineralogical composition, durability and toughness, resistance to freezing and thawing, among others. Such tests may include petrographic analysis, acid insoluble residue, micro-Deval loss, Los Angeles abrasion loss, magnesium sulphate soundness, freeze-thaw evaluation, etc. Again, it is important to note that these are index tests that provide an indication of future performance only – they must therefore be validated by field evaluation, including long-term monitoring which typically requires years of expensive, replicate testing. Once approved through this multi-step, multi-year process, sources of polish-resistant aggregates in Ontario are published on the MTO Designated Sources for Materials (DSM)[16] while KYTC publishes a List of Approved Materials (LAM)[17].

Not all Aggregates are Created Equal

Common types of natural aggregates used in asphalt surface mixtures are limestone, andesite, dolomites, diabase, sandstone, meta-gabbro, gneiss, meta-arkose, crushed siliceous river gravel, traprock, basalt, slag and quartzite[18,19,20,21]. Limestone aggregates are very common in the United States and Canada and can be less costly as compared to other aggregate types in many jurisdictions. However, limestone has been noted for its tendency to polish under traffic.

The MTO is particularly strict and currently does not permit the use of carbonate (i.e. limestone) aggregates for surface course HMA on their main highways. Guidance for the use of "Friction Courses" in Ontario is provided in Ministry Directive PHM-C-001[22]. For provincial highways with Average Annual Daily Traffic (AADT) of between 2,500 and 5,000 vehicles per day per lane, the coarse aggregate fraction of the HMA must be from an approved polish-resistant source on the DSM[16], with the resulting mix referred to as "Friction Course, FC1," while roadways experiencing greater than 5,000 vehicles per day per lane are required to use HMA incorporating polish-resistant aggregates for both fine and coarse aggregate fractions[22], referred to as "Friction Course, FC2" Although this direction was issued for provincial highways, most municipalities follow the guidelines for their roadways as well.

In Kentucky, carbonate aggregates must be used as it is the primary source of aggregate in the state. Dolomite limestone is historically considered as a premium source for meeting KYTC's friction needs. KYTC has these designations for friction classes of aggregate:

- Class A - All interstates and parkways with ADT $\geq$ 5,000 and other roads with ADT $\geq$ 15,000
- Class B - All interstates and parkways with ADT $\leq$ 5,000 and other roads between 5,000 and 15,000
- Class D – All roads with ADT < 5,000. There is no Class C designation.

Most recently to improve friction, KYTC began requiring the following when utilizing a dolomitic polish-resistant aggregate as the coarse portion of the asphalt surface mixtures: minimum of 70 percent of total combined aggregate must be Class A polish-resistant aggregate, any coarse aggregate must be Class A polish-resistant, non-dolomitic substitutes from other Class A sources may be used as direct substitutes, and all mixes are required to submit DFT testing to KYTC with any supporting documentation prior to completion of the project.

While Ontario limestones appear to be unsuitable for high traffic applications, the mineralogy of limestone in other jurisdictions is such that polish-resistance may be acceptable. Limestone aggregates containing harder, sand-sized particles may provide excellent and continuous micro-texture as the softer carbonate matrix is worn away under traffic loading[23]. The use of the Acid Insoluble Residue (AIR) test[24] has historically been used to ensure polish-resistance of aggregates by ensuring a certain percentage of non-carbonate minerals within a limestone or dolostone matrix. Larger insoluble residue percentages indicate a larger presence of siliceous minerals, which are considered more polish-resistant than carbonate materials[25] and are considered better suited for higher traffic roads[26]. The MTO utilizes AIR as a screening criterion on dolomitic sandstone sources, requiring a minimum of 45 percent non-carbonate material for acceptance[27].

In general, AIR plays an important role in the frictional properties of aggregates[26,28,29,30]. Studies indicate a positive correlation between acid-insoluble residues, particularly those greater than 75 microns, and friction values in dolomite aggregates. Skid resistance tends to increase with the amount of AIR, where sand-size residue is more significant than total residue. The size distribution of the insoluble fraction also impacts pavement friction values, with a better relationship potentially existing between total insoluble residue and friction coefficient[31]**.**

While high AIR has been shown to provide high friction and polish resistance, it is the Authors' opinion that not all high friction and polish resistance may be attributed solely to high AIR results. The use of AIR solely as an acceptance criterion may be overly limiting, thereby rejecting aggregate sources with acceptable polish resistance, and leading to increased cost. Furthermore, the volume of approved aggregate sources is dwindling with continued use. New aggregate sources and types will be required, and the historic approval processes will no longer be feasible to accurately and rapidly assess polish resistance. A new approach is needed for "the road ahead."

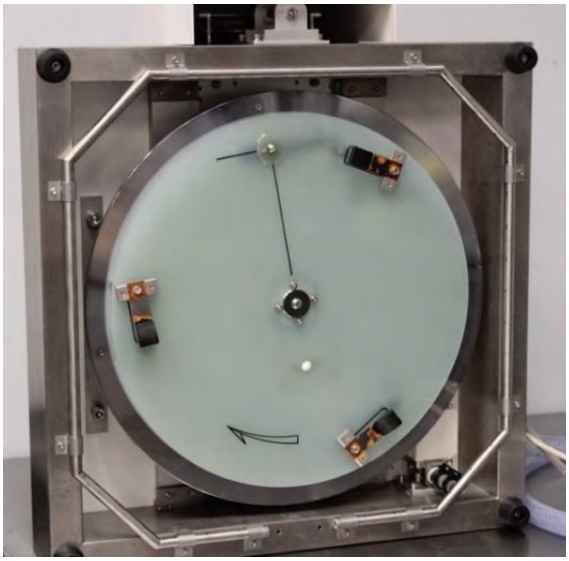
Accelerated Evaluation of Polish Resistance and Friction

An accelerated approach is required for the evaluation of new aggregate types and sources with respect to polish resistance. Furthermore, the approach should also be able to assess both aggregate and mix performance, as it is the final HMA mixture (or bituminous surface treatment) placed on the pavement that is subject to polishing effort from traffic loading and winter maintenance operations. As will be discussed herein, the combination of the Three-Wheel Polishing Device (TWPD) and Dynamic Friction Tester (DFT) presents a promising accelerated approach.

The DFT (Figure 2) was developed in Japan in the late 1990's as a next generation to the British Pendulum[32]. The device spins a loaded disc with three small rubber pads to a speed of 80 km/hr, drops the disc on the pavement surface, and measures the contact friction at various speeds as the disc slows to a stop. As such, the full slip-speed friction curve is established, and the test may be completed in either the laboratory or the field in a dry or wet condition.



(a) DFT



(b) Rubber Pads on DFT

Figure 2. Dynamic Friction Tester (DFT)

Looking to take advantage of the DFT capabilities, the National Center for Asphalt Technology (NCAT) at Auburn University developed the TWPD (Figure 3) in 2006 to provide accelerated polishing to aggregate or HMA laboratory samples. The device consists of three rubber tires that apply a constant load and speed on a pavement sample, creating a wear path that reduces the surface texture and friction.



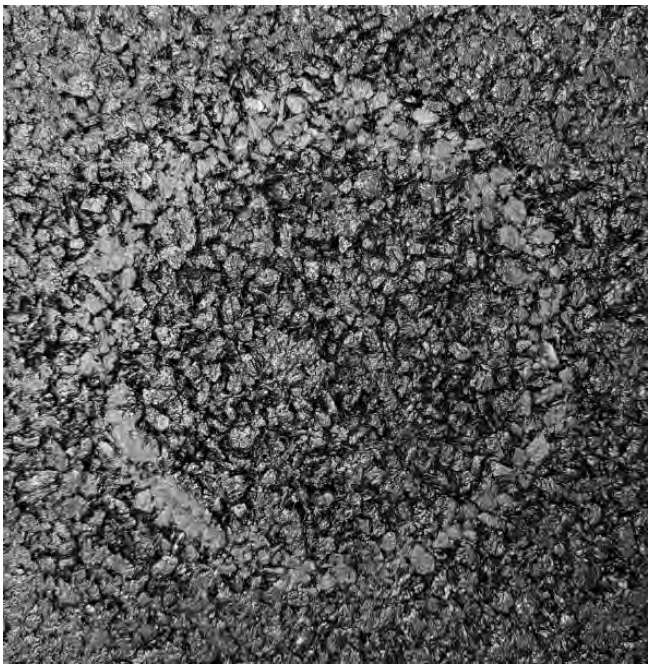


Figure 3. NCAT Three-Wheel Polishing Device (TWPD) at left and polished slab sample at right.

The total number of polishing cycles may be varied but typically ranges between 100,000 and 150,000. Friction testing can be completed at any polishing interval to evaluate early, midlife, and terminal friction performance as desired. An extensive repeatability and reproducibility study using the TWPD and DFT by NCAT[33] has led to the development of two new specifications through the American Association of State Highway and Transportation Officials (AASHTO) – R 133 for prepared aggregate specimens[34] and R 134 for compacted slab specimens of HMA[35].

Experimental Plan

Goals and Objectives

Blankenship Asphalt Tech & Training, PLLC was retained by a hot mix asphalt producer in Kentucky to evaluate an existing limestone source as a potential supply for Class A and B polish-resistant aggregates. Specific goals of the study included:

- Compare the initial and terminal DFT friction coefficients of the limestone source, referred to herein as "GLS" to a well-known and approved polish-resistant, non-carbonate source referred to herein as "HDM" before and after polishing with the TWPD;
- Analyze the effect of different DFT speeds on the friction measurements of each aggregate source and gradation before and after polishing;
- Identify if the GLS aggregate source can be a suitable replacement for HDM aggregate on Class A and Class B roadways in Kentucky;
- Understand if there is a limit to how much GLS aggregate can be used in an asphalt mixture before impacting pavement friction;
- Determine if there is a correlation between DFT measured field samples versus measured on laboratory-prepared samples; and
- Review how the GLS aggregate performs over several years using the Locked-Wheel Skid Trailer from the KYTC.

The experimental plan consisted of three phases. For Phase 1, laboratory-produced, laboratory-compacted HMA mixes were prepared and evaluated with the TWPD and DFT to compare various combinations of GLS and HDM aggregates. For Phase 2, plant-produced, laboratory-compacted HMA mixes were evaluated with the TWPD and DFT and compared to plant-produced, field-compacted HMA tested in the field with the DFT. For Phase 3, plant-produced HMA incorporating GLS aggregates and laboratory-produced HMA incorporating HDM aggregates were tested with the DFT at extended polishing effort to 1,000,000 wet cycles.

Methodology

Materials and Mixes

Table 1 summarizes the physical and chemical properties of the GLS aggregate. From the chemical analysis, the GLS minerology is predominately carbonate material (CaCO3 and MgCO3) with the remaining portion being noncarbonate.

Table 1. Summary of physical and chemical properties for Phase 1 Laboratory Comparison

Physical Tests						Chemical Analysis				
Source	Size	ABS	SP. GR. (SSD)	Soundness	LA%	Ca CO_3	Mg CO_3	SiO_2	R_2O_3	AIR
GLS	Coarse 0.5 to 0.375 in (12.5 to 9.5 mm)	1.1	2.69	1.6	16.8	54.8	12.3	25	4.3	26.9

Notes: ABS is the percentage Absorption and AIR is Acid Insoluble Residue.
CaCO3, MgCO3, SiO2, and R2O3 are the respective percentages of calcium carbonate, magnesium oxide, silicon oxide, and iron (ferric) oxide in the aggregate.
LA% is the Los Angeles abrasion loss in percentage.
Soundness means magnesium sulphate soundness.
SP. GR. (SSD) is specific gravity in the saturated surface dry state.

For Phase 1, a total of 10 mixture combinations were produced in the laboratory, compacted in the ARC, polished with the TWPD, and tested for friction with the DFT (Table 2). The optimum binder content using a PG64-22 was maintained constant at 5.8% for all mixtures and therefore should not influence the friction measurements in this case. The amount of carbonate (GLS) and non-carbonate (HDM) aggregate was varied as to see the influence of each type on polish-resistance and friction as it increases in the mixture composition. BATT-ID 23-0092 is considered the “Control” mixture for the comparisons.

For Phase 2, HMA mixture incorporating GLS aggregates was sampled from two projects near Columbia, Kentucky for laboratory polishing and friction analysis of plant-produced mix. The mixture utilized on both projects was a 0.38-inch (9.5-mm) nominal maximum aggregate size with a PG 64-22 binder. The design traffic level was Class 3 and Class B virgin aggregates were utilized on both projects.

For Phase 3, the same plant-produced HMA sampled in Phase 2, as well as a laboratory-produced HMA incorporating HDM aggregates were subjected to extended polishing (1,000,000 cycles). The aggregate gradations for the two mixes are shown in Table 3. The GLS mix contained 85 percent of the source aggregate as well as 15 percent RAP. The Control mix contained 75 percent HDM material, 10 percent GLS material (fine aggregates) and 15 percent RAP. The average AIR of the extracted aggregates for the GLS mix was 26.2 percent.

Specimen Preparation

The noted HMA mixes were heated and compacted in an Asphalt Roller Compactor (ARC), which prepares rectangular, slab-type specimens required for TWPD polishing and DFT testing. The curved steel compaction head of the ARC oscillates over the loose HMA mix and simulates the effort of a static steel wheel roller. The mold in the ARC was charged with sufficient material to achieve a target density of between 92 and 94 percent of theoretical maximum density (Gmm) within the desired slab thickness of 50-mm (2-inch) with dimensions of 500 by 400-mm (20 by 15-inches).

Table 2. Mixture Composition for Phase 1 Laboratory Comparison

BATT ID	HDM Coarse	HDM WLS	Other WLS	Natural Sand	RAP	Non - Polishing (NP) RAP	Total HDM Material	DFT Friction After 150,000 Passes
23-0092	25%	20%	37%	0%	18%	0%	**45%**	**0.330**
23-0093	25%	20%	22%	15%	18%	0%	**45%**	**0.370**
23-0094	35%	35%	12%	0%	18%	0%	**70%**	**0.405**
23-0095	25%	30%	10%	15%	20%	0%	**55%**	**0.375**
23-0096	25%	30%	10%	15%	0%	20%	**55%**	**0.390**
23-0125	20%	35%	10%	15%	0%	20%	**55%**	**0.387**
BATT ID	**GLS Coarse**	**GLS LSS**	**Other WLS**	**Natural Sand**	**RAP**	**Non-Polishing (NP) RAP**	**Total GLS Material**	**DFT Friction After 150,000 Passes**
23-0126	25%	30%	10%	15%	0%	20%	**55%**	**0.370**
23-0127	25%	30%	10%	15%	20%	0%	**55%**	**0.370**
23-0167	35%	35%	12%	0%	18%	0%	**70%**	**0.350**
23-0203	35%	35%	0%	10%	0%	20%	**70%**	**0.355**

Notes: Sample 23-0092 is considered the Control mix for comparison purposes.
RAP is Reclaimed Asphalt Pavement, WLS is Washed Limestone Screenings, and LSS is Limestone Screenings.

Table 3. Mix Design Comparison for Phase 3 HMA Mixtures

Sieve (in)	HDM Aggregates	GLS Aggregates
¾	100	100
½	100	100
3/8	90	95
#4	58	61
#8	39	40
#16	25	25
#30	17	16
#50	12	12
#100	8	9
#200	5.7	7.3
P_b	6.3%	6.1%
Binder Grade	PG 64-22	PG 64-22

Polishing & Friction Testing

For Phase I and 2, the laboratory slabs were subjected to friction using the DFT (Figure 2) to establish the baseline friction value. Subsequently, the slabs underwent the polishing process using the TWPD (Figure 3). After each polishing period, friction measurements were taken using the DFT to assess the friction properties of each slab. Friction measurements were obtained at intervals of 5,000, 25,000, 75,000, and 150,000 wet polishing cycles. This testing approach may yield insights into the frictional performance of the slabs at various polishing stages, which could facilitate an understanding of their durability and resistance to polishing with some prediction of future polishing. For Phase 3, additional polishing and friction testing was completed at 200,000, 400,000, 800,000, and 1,000,000 cycles.

For Phase 2, field friction testing with the DFT occurred on June 22, 2023, with overcast conditions and air temperatures ranging from 65 to 70°F.

Locked-Wheel Skid Trailer (LWST) Testing

Skid resistance is part of the pavement management strategy in Kentucky. The Operations and Pavement Branch collects and analyzes data to measure the performance of pavements, maintenance systems, and transportation systems. Historically, KYTC has utilized the Locked-Wheel Skid Trailer (LWST) with a ribbed tire for field friction assessment. More recently, KYTC is also conducting continuous network-level evaluation using the Sideway-Force Coefficient Routine Investigation Machine (SCRIM®) as they further develop their mature Pavement Friction Management (PFM) program.

For the current investigation, Skid Numbers (SN) were recorded with the LWST at the Phase 2 project sites in the left wheel path of each lane at 0.5-mile intervals annually between 2019 and 2023.

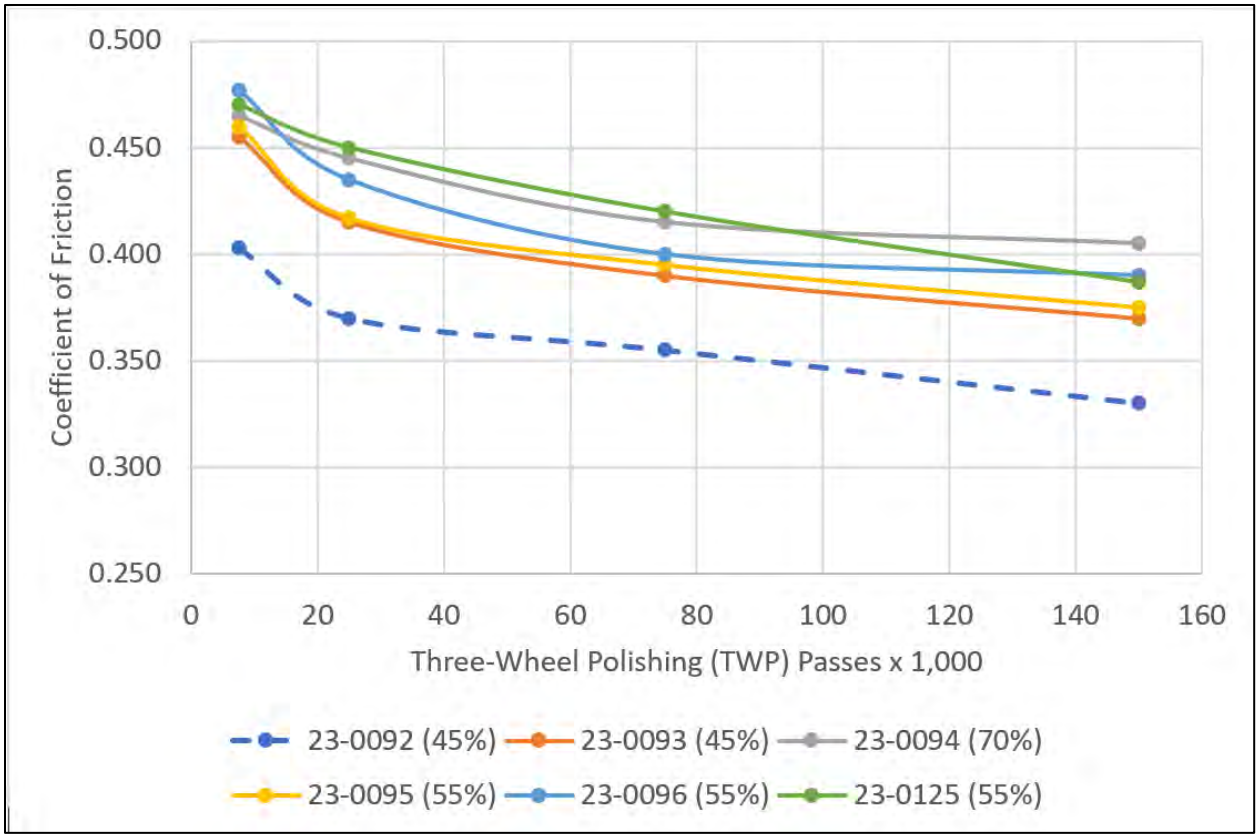
Results

Phase 1 – Laboratory-Prepared, Laboratory-Compacted Mixes

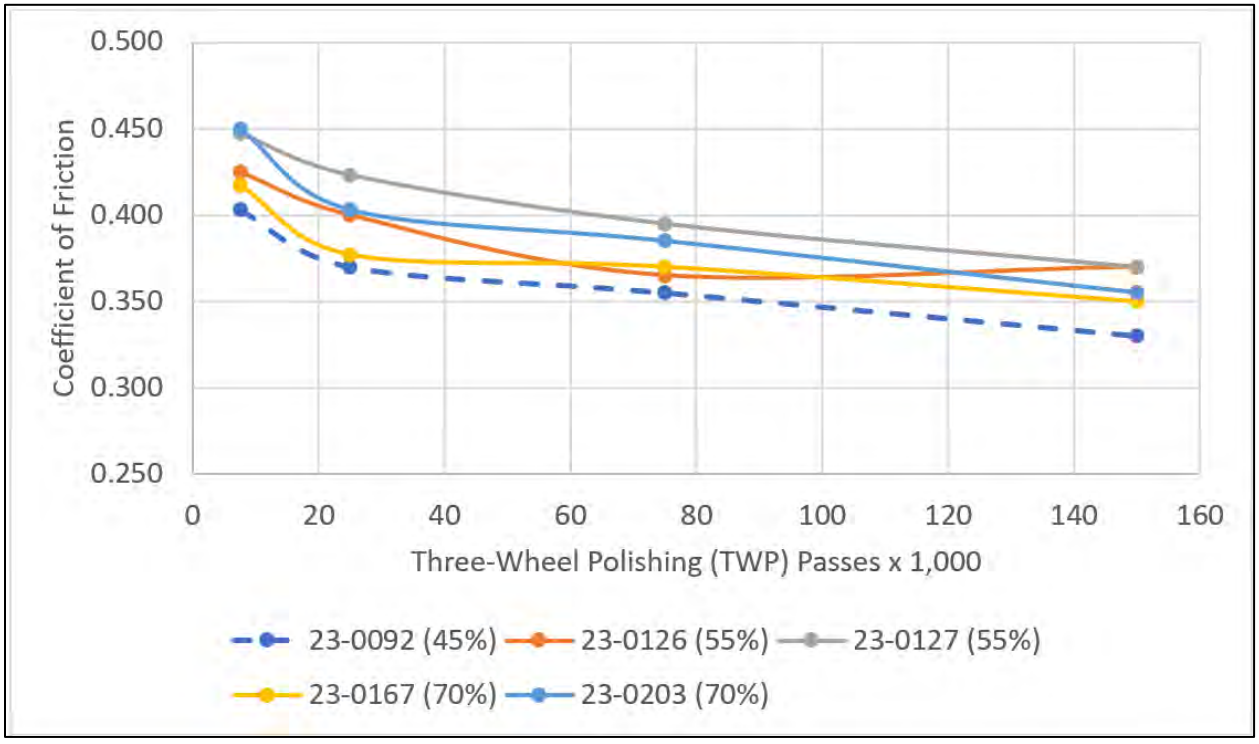
Terminal DFT friction values (60 km/hr) after 150,000 wet polishing cycles in the TWPD are also presented in Table 2, while the decrease in DFT friction with increasing polishing effort is shown in Figure 4. The Control mix containing 45 percent of the approved non-carbonate HDM aggregates yielded a terminal friction value of 0.330.

For mixtures containing increased percentage of HDM aggregates, terminal friction ranged between a low of 0.370 (55 percent HDM aggregates) to 0.405 (70 percent HDM aggregates) with friction increasing with increasing non-carbonate aggregate percentage as expected.

For mixtures containing the carbonate GLS aggregates, terminal friction ranged between a low of 0.355 (70 percent GLS aggregates) to 0.370 (55 percent GLS aggregates). As such, terminal friction decreased with increasing carbonate aggregate percentage, which could also be expected, although all mixtures retained terminal friction above the Control value.



a) Dynamic Friction Test Results on Mixtures with HDM (non-carbonate) Aggregates at 60 km/hr



b) Dynamic Friction Test Results on Mixtures with GLS (carbonate) Aggregates at 60 km/hr

Figure 4. Dynamic Friction Test Results of Mixtures Produced during Phase 1

Evaluation of Table 2 and Figure 4a provides some interesting insights concerning mixes containing the HDM aggregates:

- Comparing Control (23-0092) versus 23-0093: Both mixtures have the same amount of HDM aggregate and RAP. The only difference is that 23-0093 uses 15% natural sand and 19% less Washed Limestone Screenings (WLS) from a different (Other) source. This infers that the hardness of the natural sand may be a friction promoter as compared to the WLS.
- Comparing Control (23-0092) versus 23-0094: Mix 23-0094 uses the largest amount of HDM aggregate at 70% and 25% less WLS from a different (Other) source. The RAP content is the same in both mixtures. This aggregate blend had the highest reported friction of all mixtures.
- Comparing 23-0095 versus 23-0096 versus 23-0125: All three of these mixtures have 55% HDM aggregates along with 10% Other WLS and 15% natural sand. However, 23-0095 uses RAP while 23-0096 and 23-0125 uses Non-Polishing (NP) RAP. Mix 23-0095 had a terminal friction value of 0.375; 23-0096 was 0.390; 23-0125 was 0.387. There are some minor differences in the coefficient of friction among these three mixtures, and all have higher coefficient of friction compared to the control. Note NP RAP mixtures 23-0096 and 23-0125 have improved friction over 23-0095 with no RAP. This shows the value of RAP (for friction) and how we can use DFT to identify/classify these NP RAP sources.

Evaluation of Table 2, Figure 4a and Figure 4b provides the following interesting insights when comparing mixes with either HDM or GLS aggregates:

- Comparing 23-0126 versus 23-0096: Both mixes had the same overall percentage of coarse aggregate, screenings, natural sand, and non-polishing RAP. The only difference between 23-0126 and 23-0096 is the source material for 55 percent of the blend. The mixture containing 55 percent GLS aggregate had slightly lower terminal friction (0.370) as compared to the mixture containing 55 percent HDM aggregate (0.390), with both exceeding the Control mix (0.330).
- Comparing 23-0127 versus 23-0095: Similar to the previous finding, both mixes had the same overall percentage of coarse aggregate, screenings, natural sand, and RAP. The mixture containing 55 percent GLS aggregate had identical terminal friction (0.370) as compared to the mixture containing 55 percent HDM aggregate (0.375), with both exceeding the Control mix (0.330).
- Comparing 23-0167 versus 23-0094: Mix 23-0167 containing 70 percent of GLS aggregate outperformed the control in terms of terminal friction (0.350). The only difference between 23-0167 and 23-0094 is the source of coarse aggregate and WLS source. Both had identical Other WLS and RAP percentages. In this instance, the HDM aggregate source with a terminal friction of 0.405 outperformed the GLS blend (0.350). The 70 percent GLS aggregate blend performance decreased as compared to the 55 percent GLS aggregate blend in the previous comparison.

Finally, some aggregate blends such as Mixes 23-0094, 23-0096, and 23-0126 displayed flatter polishing slopes as compared to the other mixes and control. A flatter slope suggests that these aggregate blends will polish a lesser (slower) rate as compared to the other blends and promise to maintain friction longer.

Phase 2 – Plant Produced, Laboratory-Compacted Mixes & Field Testing

Initial Field Friction Testing with Dynamic Friction Tester

Figure 5 shows the initial surface friction findings at various speeds on the 9.5-mm NMAS GLS mixture on all field test sections. The mixtures exhibited friction values ranging from 0.35 to 0.45 on recently constructed pavements with minimal traffic, known as “initial friction”. These values are generally lower compared to pavements that have been subjected to 6-12 months of traffic. This disparity can be attributed to the gradual wearing away of the binder layer coating the asphalt, exposing the aggregate and consequently increasing surface friction, which is referred to as "peak friction.” It is anticipated that friction will continue to increase after approximately one year.

Notably, Location #5 on KY-61/80 exhibited a lower friction value compared to the other locations. The test was conducted in the right turning lane onto another highway. It is hypothesized that the lower traffic volume polished the binder film off less than the other lanes thus resulting in a lower coefficient of friction.

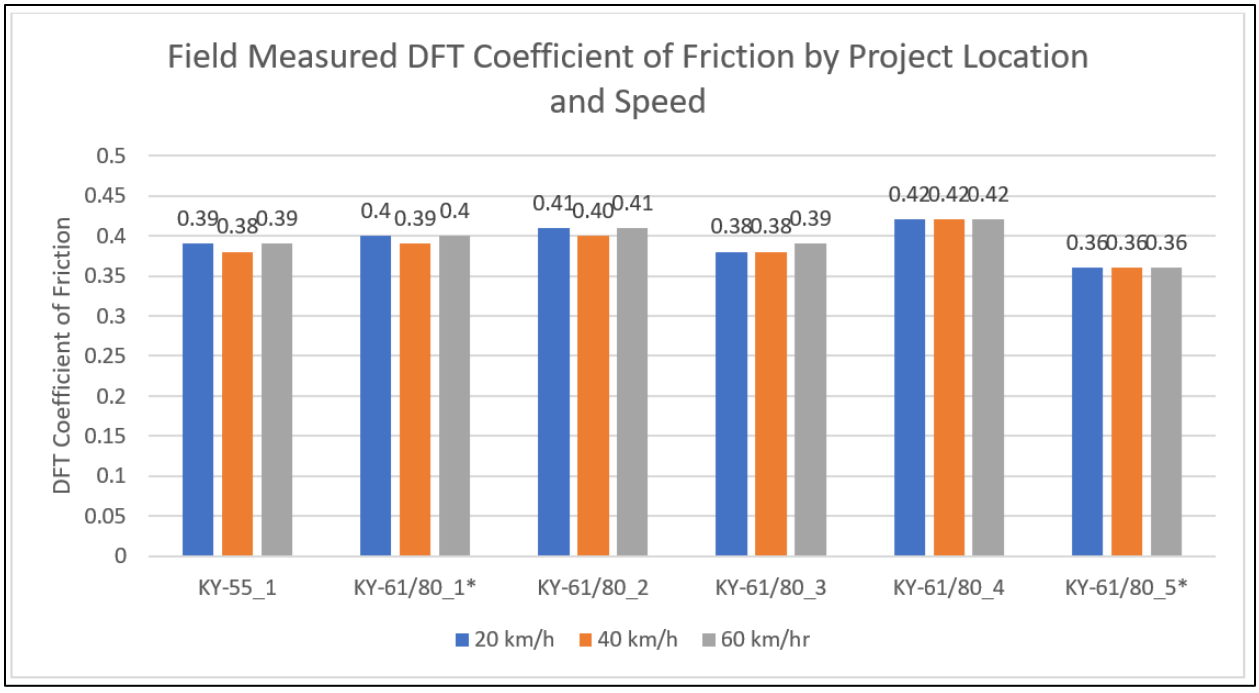
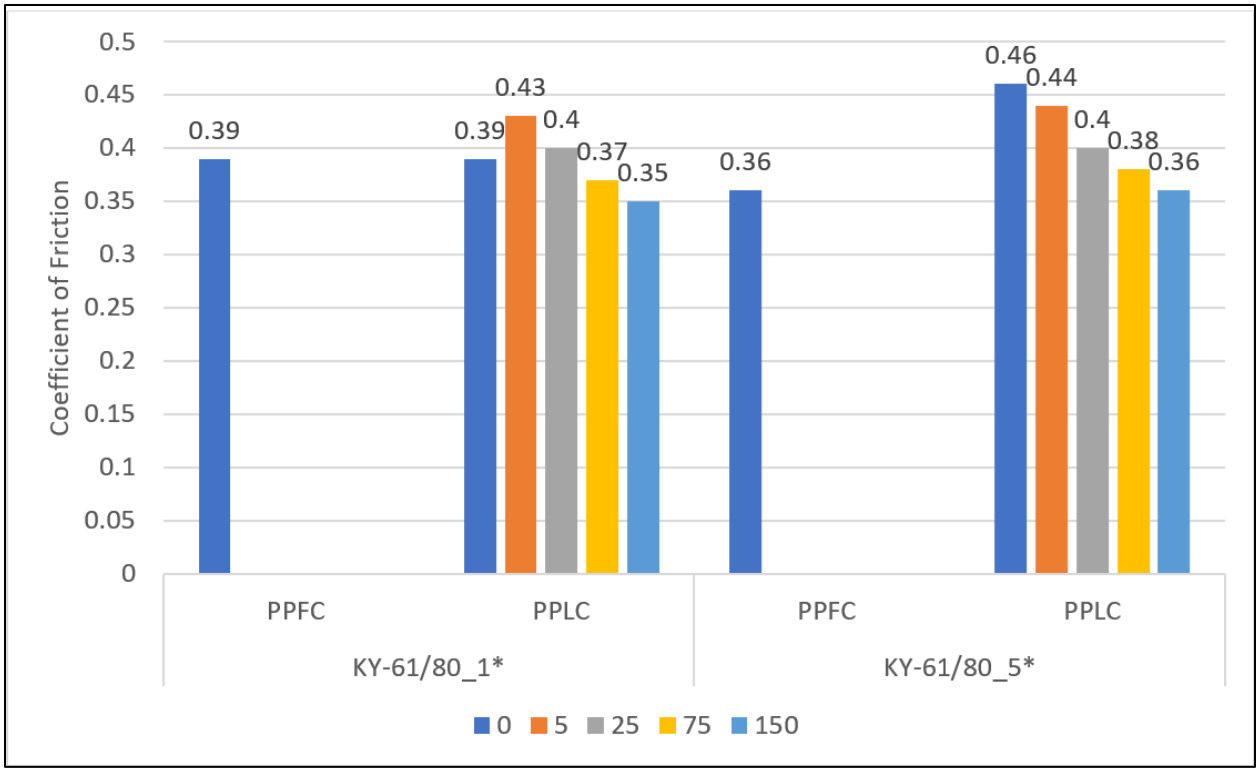


Figure 5. Initial Friction from Field Dynamic Friction Testing at Multiple Project Locations

Laboratory Testing of Plant-Produced Mixture

Figure 6 shows the DFT coefficient of friction test results from slab samples produced in the laboratory from the two plant produced mixes following the same TWPD polishing schedule as Phase 1. The respective field DFT friction values are also shown. Test results from both sections resulted in consistent frictional properties throughout the polishing passes. The final frictional values for both sections resulted in a final surface friction of 0.35 for sampled mixture from location #1 and 0.36 for the mixture sampled from location #5.



Note: the legend represents the number of polishing cycles in the Three-Wheel Polishing Device (x1000)

Figure 6. Plant-Produced, Laboratory-Compacted (PPLC) vs Plant-Produced, Field-Compacted (PPFC) Friction Values from Dynamic Friction Tester

As shown, Location 1 displays great correlation between the field measured coefficient of friction (initial, i.e. time zero) and laboratory measured coefficient of friction (initial, no passes in the TWPD). However, Location 5 does not have that same correlation. It is hypothesized that the laboratory slabs from location #5 experienced a phenomenon sometimes seen in the laboratory where the asphalt roller compactor can leave a rougher texture on the surface after compaction.

Locked-Wheel Skid Trailer Testing

Friction measurements were conducted 2019, 2020, 2021, 2022, and 2023. Figure 7 shows the ribbed friction number of these six projects against cumulative traffic. There is a general decrease in ribbed friction number over time which is typical. There is some minor noise in the data because in some cases, friction measurements were made in the summer months (June or July) and autumn months (September or October) of the same year (approximately 5 months apart). It is known that temperature and environmental conditions can impact friction measurements made in the field. The data does show an increase in ribbed friction number in October when compared to June when testing was conducted in the same year.

All ribbed friction numbers are greater than 28, which is within the “no further action is necessary” range by KYTC.

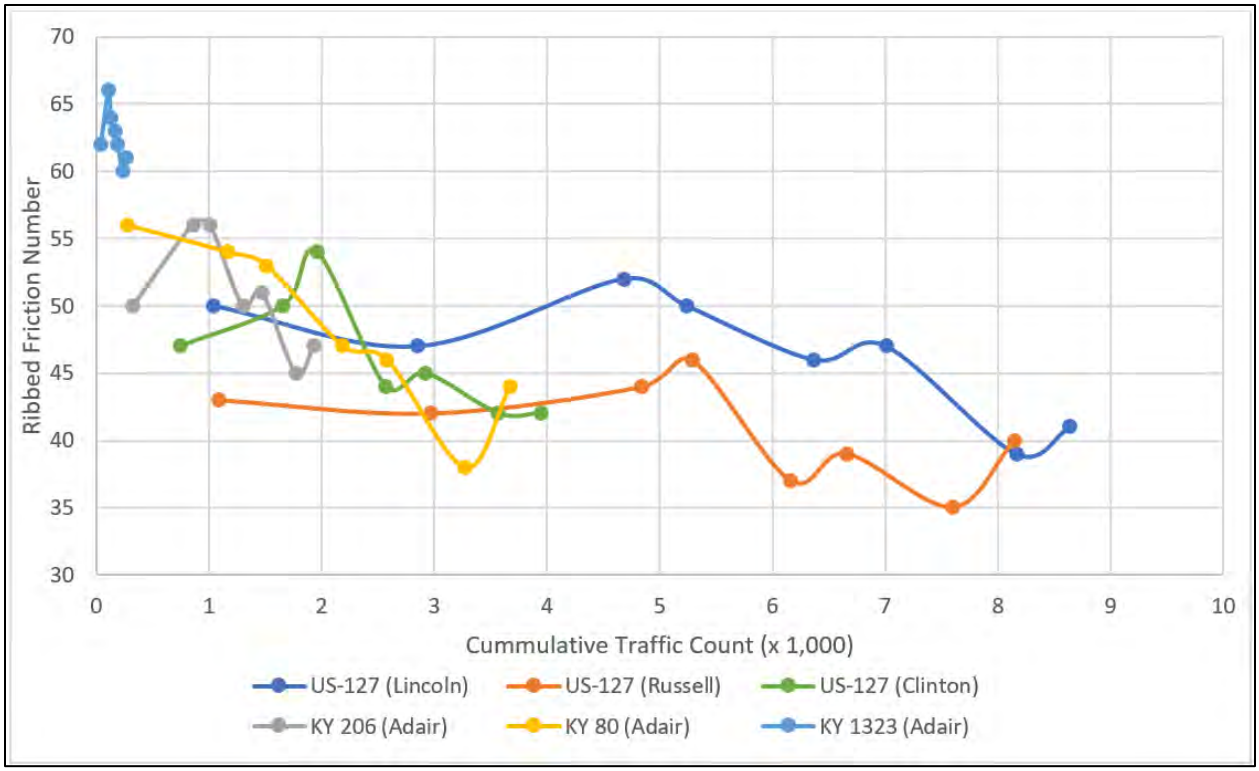


Figure 7. Ribbed Tire Friction Number vs. Cumulative Traffic Count on Selection of Kentucky Projects with GLS Aggregate

Mission to 1 Million – Extended Polishing

DFT friction values at 40 km/hr for the prepared HMA specimens in Phase 3 are provided in Table 4.

Table 4. Dynamic Friction Tester (DFT) Friction at 40 km/hr for Phase 3

Three-Wheel Polishing Device (TWPD) Passes	GLS Slab 1	GLS Slab 2	HDM Slab 1	HDM Slab 2
1	0.41	0.38	0.37	0.44
5,000	0.41	0.40	0.43	0.50
25,000	0.35	0.37	0.40	0.44
75,000	0.32	0.37	0.39	0.44
150,000	**0.32**	**0.40**	**0.36**	**0.41**
200,000	0.29	0.41	0.32	0.38
400,000	0.25	0.45	0.29	0.37
600,000	0.22	0.36	0.28	0.34
800,000	0.22	0.31	0.26	0.31
1,000,000	**0.27**	**0.29**	**0.24**	**0.28**

The Table 4 data are plotted on a logarithmic scale in Figure 8.

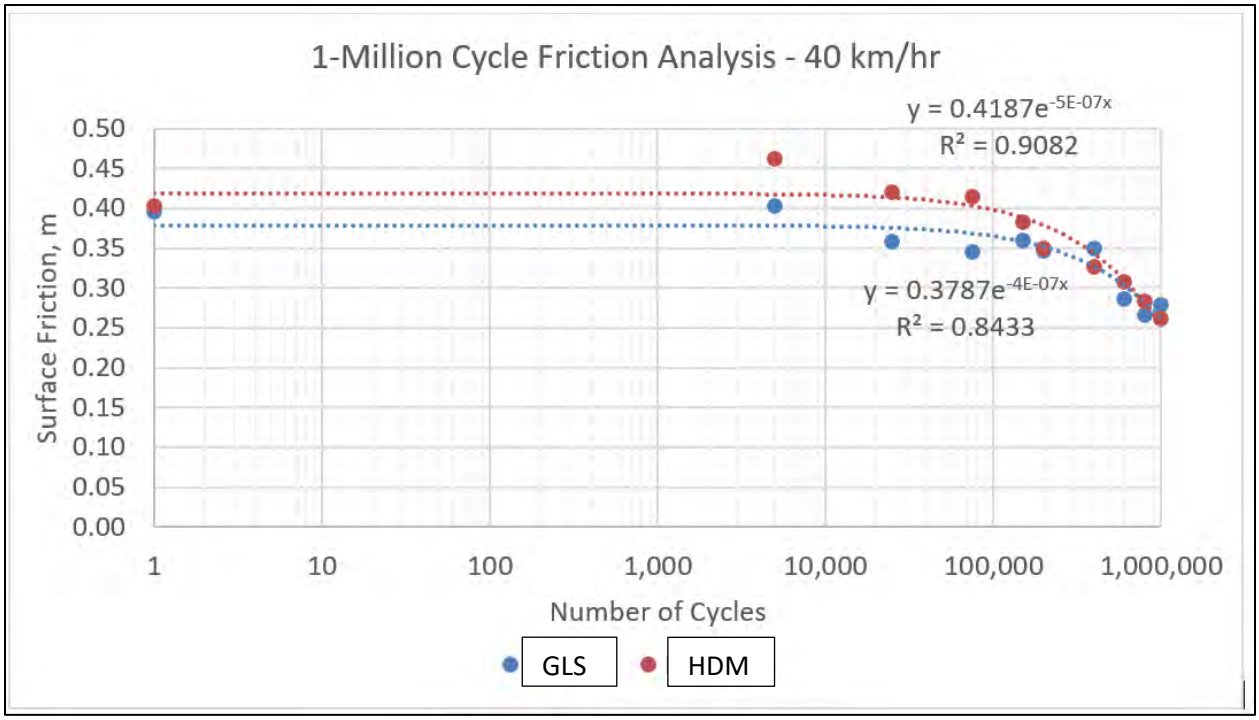


Figure 8. Dynamic Friction Test (DFT) Results at 40 km/hr to 1 Million Polishing Cycles for GLS and HDM Mixes

Error! Reference source not found. Figure 8 shows that the HDM and GLS mixes have similar initial coefficient of friction although slightly higher for the HDM mixture. However, after 1,000,000 cycles the coefficient of friction for the GLS aggregate is greater than the HDM aggregate. The switch occurs somewhere around 200,000 cycles. The slope of coefficient of friction from 5,000 cycles to 1,000,000 cycles is greater for the HDM aggregate than the GLS aggregate, again potentially suggesting better polish resistance.

Discussion

The test results from the aggregate screening laboratory study (Phase 1) align with the research hypothesis that the GLS aggregate can be used in place of the HDM material and achieve acceptable friction measurements as quantified using the TWPD and DFT. The field study shows that the GLS aggregate can be placed in the field successfully and achieve adequate friction as measured using the DFT in the field and on plant-produced laboratory compacted samples (Phase 2). The follow up field study by the KYTC using the LWST has also shown that the GLS aggregate has been successfully used on several projects in Kentucky and the early friction and later friction performance is adequate and within their levels where no further action is necessary. Finally, the extended polishing effort in Phase 3 showed that both GLS and HDM mixtures performed well after 1,000,000 cycles with the GLS mix showing slightly better polish resistance. Clearly, the use of AIR alone for aggregate screening may not be appropriate for all carbonate aggregate sources.

As with any research study, there are constraints and limitations. The laboratory research study is constrained by the mixtures that were evaluated and the percentages of each material (either HDM or

GSLL) that were used. RAP can also affect the results and must be isolated and properly stockpiled to avoid an "anything goes pile." Also, only one binder source was utilized for this research study. Temperature and weather can impact friction measurements. In the laboratory, these factors can be controlled but, in the field, one must document the weather and temperature when measurements are made.

Recommendations

The results of this investigation are preliminary and ongoing, however, have provided several interesting insights into the polishing and frictional characteristics of aggregates with differing mineralogical composition. To date, the work has led to the following recommendations:

- The use of the **TWPD + DFT** is recommended as a performance-based screening tool for candidate aggregates (AASHTO R 133) and mixes (AASHTO R 134);
- The continued reporting **AIR** is recommended as an index property, but agencies should not rely on it alone for acceptance;
- Expanded field validation comparing **DFT**, **LWST**, and **SCRIM** results is recommended to allow comparison of historical friction measures.
- The significance of **friction-loss slope** as an indicator of long-term polishing resistance should be investigated more thoroughly; and
- The role of **RAP and non-polishing RAP** in a more systematic manner is also recommended.

Summary & Closure

Maintaining adequate friction between the tire and pavement surface is critical to the safe operation of all vehicles. Historically, many road agencies have identified sources of polish-resistant aggregates from legacy data or multi-year monitoring efforts. Unfortunately, these approaches may no longer be feasible to accurately or rapidly evaluate polish resistance for the "road ahead" which will include unknown, but most likely more intense and frequent loading associated with the onset of Autonomous Vehicles (AVs), Connected Autonomous Vehicles (CAVs), and Electric Vehicles (EVs).

To accelerate the evaluation process, the use of the NCAT Three-Wheel Polishing Device (TWPD) and Dynamic Friction Tester (DFT) offers a promising laboratory approach. At present, 150,000 cycles are used to assess the polish resistance of aggregates in compacted HMA samples. As an exercise, extended TWPD to 1,000,000 cycles was utilized to compare the polish resistance of HMA mixtures produced with varying percentages of two different aggregate sources. While the carbonate GLS mix polished slightly more than the non-carbonate HDM mix at the current 150,000 cycles, greater polish resistance after 1 million polishing cycles was observed with the GLS material. The use of the slope of the DFT friction versus the number of polishing cycles curve appears to have promise for identifying aggregate polish resistance and should be considered during the evaluation process.

The study also provided insights into the use of Acid Insoluble Residue (AIR) testing. Based on results obtained, it is recommended to use AIR as an index test to be reported but waived if the TWPD and DFT results are acceptable.

While routine TWPD polishing to 1 million cycles is not recommended due to excessive time and machine wear, the results did suggest that long-term polishing performance of aggregates is complex. Overall, the use of the TWPD and DFT in the laboratory presents a promising approach for the accelerated evaluation of HMA mixtures and new aggregate sources, with the goal of better managing pavement friction and saving lives on North American roadways.

References

[1] https://www.blg.com/en/insights/2021/12/autonomous-vehicles-canadas-readiness-for-the-future

[2] https://pmc.ncbi.nlm.nih.gov/articles/PMC8611256/

[3] https://www.sciencedirect.com/science/article/pii/S209575642100043X

[4] https://thedriven.io/2024/05/03/are-evs-really-much-heavier-than-their-ice-equivalents/

[5] R.V. Siddharthan, M. Nasimifar, X. Tan, et al. "Investigation of impact of wheel wander on pavement performance" in Road Materials and Pavement Design, 18 (2017), pp. 390-407.

[6] https://tc.canada.ca/en/road-transportation/statistics-data/canadian-motor-vehicle-traffic-collision-statistics/2023/canadian-motor-vehicle-traffic-collision-statistics-2023

[7] American Society of Civil Engineers. "A Comprehensive Assessment of America's Infrastructure." 2025 Report Card for America's Infrastructure. Available at https://infrastructurereportcard.org/wp-content/uploads/2025/03/Full-Report-2025-Natl-IRC-WEB.pdf

[8] https://highways.dot.gov/sites/fhwa.dot.gov/files/Pavement%20Friction%20Management_508.pdf

[9] https://highways.dot.gov/safety/rwd/keep-vehicles-road/pavement-friction/fhwa-characterizing-road-safety-performance-using

[10] Merritt, D.K., Lyon, C., Persaud, B.N. and Torres, H.N. "Developing Crash Modification Factors for High-Friction Surface Treatments," Report FHWA-HRT-20-061, Federal Highway Administration (FHWA), US Department of Transportation, McLean, Virginia (2020). Available at https://rosap.ntl.bts.gov/view/dot/54072. Accessed April 22, 2026.

[11] Musey, K., Parl, S., Louwers, E. "Economic Feasibility Analysis of High Friction Surface Treatments in Pennsylvania." 18th International Conference Road Safety on Five Continents (RS5C 2018), Jeju Island, South Korea, May 16-18, 2018. Available at https://www.diva-portal.org/smash/get/diva2:1203813/FULLTEXT01.pdf.

[12] Yang, G., Wang, K.C.P., LI, J.Q., Wang, G., Liu, W., Yang, X. "Crash Reduction Benefits of High Friction Surfacing Treatments (HFST)." International Conference on Transportation and Development, 2022.

[13] Wilson, B.T., Brimley, B.K., Mills, J., Zhang, J., Mukhopadhyay, A., Holzshuher, C. "Benefit–cost analysis of Florida high-friction surface treatments." Transportation Research Record: Journal of the Transportation Research Board, 2250, 54–62, 2016.

[14] Goodman, S.N. and Potter, R. "Pavement Friction Management for Safer Roads: An International Overview to Guide Canadian Implementation," Annual Conference of the Canadian Association of Road Safety Professionals, Quebec City (2025).

[15] Kowalski, K. J., McDaniel, R. S., & Olek, J. (2008). Development of a Laboratory Procedure to Evaluate the Influence of Aggregate Type and Mixture Proportions on the Frictional Characteristics of Flexible Pavements. Journal of the Association of Asphalt Paving Technologists, 77, 35-70.

[16] Ontario Ministry of Transportation (MTO). Designated Sources for Materials (DSM). Available at https://www.library.mto.gov.on.ca/SydneyPLUS/TechPubs/Portal/tp/mtoDSM.aspx.

[17] Kentucky Transportation Cabinet (KYTC). List of Approved Materials (LAM). Available at https://transportation.ky.gov/Materials/Documents/LAM.PDF.

[18] Rachakatla, P. (2000). Application of Relational Database Principles for Rating Bituminous Coarse Aggregates with Respect to Frictional Performance. Lubbock: Texas Tech University.

[19] Skerritt, W. H. (1993). Aggregate Type and Traffic Volume as Controlling Factors in Bituminous Friction. Transportation Research Record 1418, 22-29.

[20] Kogbara, R. B., Masad, E. A., Kassem, E., Scarpas, A., & Anupam, K. (2016). A State-of-the-Art Review of Parameters Influencing Measurement and Modeling of Skid Resistance of Asphalt Pavements. Construction and Building Materials(114), 602-617.

[21] Rogers, C., Gorman, B and Lane, B. "Skid-Resistant Aggregates in Ontario," Report MERO-005, Ontario Ministry of Transportation (MTO), Materials Engineering and Research Office (MERO), Toronto, Ontario (2003).

[22] Ontario Ministry of Transportation (MTO). Ministry Directive PHM-C-001, "The Use of Surface Course Types on Provincial Highways," Toronto, Ontario (December 12, 2014).

[23] Burnett, W. C., Gibson, J. L., & Kearney, E. J. (1968). Skid Reistance of Bituminous Mixtures. Highway Research Record, 12.

[24] ASTM D3042. "Standard Test Method for Insoluble Residue in Carbonate Aggregates." ASTM International, West Conshohocken, Pennsylvania.

[25] Kandhal, P. S., Parker, F., & Mallick, R. B. (1997). Aggregate Tests for Hot Mix Asphalt: State of the Practice. Auburn: National Center for Asphalt Technology.

[26] Sherwood, W. C., & Mahone, D. C. (1970). Predetermining the Polish Resistance of Limestone Aggregates. *Highway Research Record*, 10.

[27] OPSS 1003. Material Specification for Aggregates – Hot Mix Asphalt." Ontario Ministry of Transportation, Toronto, Ontario.

[28] Zaniewski, J. P., & Mason, C. (2006). Evaluation of Non-Polishing Aggregate Criteria for Various Traffic Levels and Low-Speed Road Conditions. Morgantown: West Virginia University.

[29] McCasland, W. (1972). Study of the Wearability and Polish Resistance of Oklahoma's Coarse Aggregates. Oklahoma City: Oklahoma Department of Highways.

[30] Kandhal, P. S., & Bishara, E. A. (1992). Evaluation of Limestone Aggregates in Asphalt Wearing Courses - Phase II. Auburn: National Center for Asphalt Technology.

[31] West, T. R., & Cho, K. H. (2001). Development of a Procedure to Identify Aggregate for Bituminous Surfaces in Indiana. West Lafayette: Joint Transportation Research Program - Purdue University.

[32] Saito, K. et al. "Development of Portable Tester for Measuring Skid Resistance and Its Speed Dependency on Pavement Surfaces," Transportation Research Record No. 1536 (1), Transportation Research Board, National Academies, Washington, D.C. (1996).

[33] Heitzman, M., Gu, F. and Welderufael, A. "Three Wheel Polishing Device and Dynamic Friction Tester Accelerated Laboratory Friction Testing Repeatability and Reproducibility Study," NCAT Report 19-05, National Center for Asphalt Technology (NCAT) at Auburn University, Alabama (2019).

[34] AASHTO R 133. "Standard Practice for Sample Preparation and Polishing of Unbound Aggregates for Dynamic Friction Testing." American Association of State Highway and Transportation Officials. Washington, D.C.

[35] AASHTO R 134. "Standard Practice for Sample Preparation and Polishing of Asphalt Mixture for Dynamic Friction Testing." American Association of State Highway and Transportation Officials. Washington, D.C.