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STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

EVALUATION OF LABORATORY TESTS TO QUANTIFY FRICTIONAL PROPERTIES OF AGGREGATES

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16. Abstract

A research study has been conducted to evaluate the existing MD SHA hot-mix asphalt aggregate friction testing procedure and provide recommendations for modifications or replacement. Phase 1 of the study consisted of a literature review and a correlation analysis of existing aggregate friction and other aggregate property data. As a result of phase 1, it was determined that the existing British Wheel/Pendulum test procedure, along with a new procedure would be investigated. Phase 2 of the study focused on development of an aggregate screening procedure, refinement of the British Wheel/Pendulum procedure and development of the new test procedure utilizing the NCAT Polisher and Dynamic Friction Tester. New draft MSMT specifications have been developed for the test procedure and a new aggregate friction test program is ready for implementation by MD SHA.

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EXECUTIVE SUMMARY

This study provides a summary of a research project undertaken by the Maryland State Highway Administration (MD SHA) to evaluate laboratory methods used to quantify the frictional qualities of aggregates used in hot-mix asphalt (HMA) pavements. The project began in January 2006 and ended in March 2010. Two primary drivers for conduct of this research were (1) operational and reliability problems with the frictional property evaluation method used in Maryland and (2) the Office of Materials Technology (OMT) proposed move to a new Hanover Facility. In order to meet the objectives of this study, the Research Team undertook a two phase process.

Phase 1 involved an in-depth literature review of existing practice related to pavement friction testing, both in the laboratory and in the field. The goal of the literature review was to examine existing Department of Transportation practice and evaluate if there were test procedures that show promise to determine aggregate friction properties.

In addition, an analysis was conducted of legacy SHA aggregate friction laboratory testing data to determine the correlation(s) of existing test procedures to aggregate friction values. At the conclusion of phase 1, options for further evaluation were presented to SHA. As a result, a decision was made to pursue replacement of the Maryland Track with new test equipment and procedures.

Phase 2 of the project consisted of three primary tasks. These were as follow:

1. Development of a revised aggregate acceptance procedure based upon the correlations developed under phase 1.
2. Variability study and test improvement process for the British Wheel and British Pendulum Tester.
3. Procurement of the National Center for Asphalt Technology (NCAT) Polisher and Dynamic Friction Tester (DFT), evaluation of test variability, and development of test procedures and specifications.

As a result of phase 2, a draft aggregate acceptance specification has been developed, a new test procedure for British Wheel/Pendulum has been developed, new polishing test equipment has been procured and implemented, and new test procedures have been developed.

The summary and conclusions resulting from the study are:

- There is no laboratory test used by a state DOT that can predict aggregate friction field performance with a high degree of certainty.
- The British Pendulum Tester (BPT) is a fairly robust test with low variability associated with the device and operator.
- The control specimens for the British Pendulum Tester are used as a means to judge the variability of the test machinery and identify when the system is not working as

required. It is essential that MD SHA establish a control specimen chart to document the performance of the control specimens for each test performed and create a mechanism for flagging data that does not meet test requirements. The most robust check on these values would be a review of these data to check the entire polish curve at each time period to determine if the values are within an expected range.

- The BPT is small, portable, easy to use, and is commonly accepted as a laboratory test of skid resistance.
- The combination of the NCAT polisher and DFT provides another robust means for evaluating aggregate friction characteristics.
- The DFT is also compact, portable, and easy to handle.
- The DFT measures friction as a function of speed and is the only instrument directly measuring the coefficient of friction.
- The DFT can be used in the field as well as in the laboratory making it possible to pursue further study to equate results of testing with the DFT in the laboratory with field performance of aggregates.

As a result of this study, the project team concludes that the NCAT Polisher and DFT combination could be a viable test procedure for Maryland to determine aggregate friction values. As a result of this study, two draft testing specifications have been developed. The specifications are included in Appendix B and C.

In order to implement these test procedures, testing should be conducted by MD SHA to determine the range of friction values for MD SHA sources. These data, along with historical data stored by MD SHA and BPT test results, should be used to determine breakpoints for the coefficient of friction value that can be used to determine high polish values.

In addition, it is recommended that a study be performed to correlate lab derived aggregate friction values with field performance of as-placed HMA mixtures. With this correlation, lab results can be more closely tied with field performance to enable better selection and control of aggregates for high polish value HMA mixtures.

CHAPTER 1. INTRODUCTION

1.1. Background

This study provides a summary of a research project undertaken by the Maryland State Highway Administration (MD SHA) to evaluate laboratory methods used to quantify the frictional qualities of aggregates used in hot-mix asphalt (HMA) pavements. The project began in January 2006 and ended in March 2010. Two primary drivers for conduct of this research were (1) operational and reliability problems with the frictional property evaluation method used in Maryland and (2) the Office of Materials Technology (OMT) proposed move to a new Hanover Facility.

Prior to conduct of this project, a number of quarries whose aggregates typically achieved high friction ratings experienced a reduction in the aggregate friction rating. These quarries represent a significant portion of MD SHA's high polish HMA production tonnage warranting a thorough and in-depth evaluation of the equipment and test procedures used to develop MD SHA's results. It was noticed that using the Maryland Track apparatus, test results were generally repeatable for average values, while the variability within a given test was high.

At the initiation of the study, the Maryland Track equipment was very old and prone to breakdowns. In addition, throughput for the test apparatus was limited to seven (7) quarry sources every two to three (2-3) months. This turnaround time and the number of active aggregate sources for MD SHA limited Polish Value (PV) testing to once every three (3) years per source which was deemed insufficient to monitor the variability in the quality of aggregates produced from a typical quarry operation.

In addition to these issues, OMT was scheduled to move from Lutherville, MD to Hanover, MD. This move required the existing track be condemned, replaced, or totally retooled for use in the new location. Therefore, a key goal of this research was to develop standards that are applicable to results from a new or retooled MD Track or other device and test method that replace the MD Track.

1.2. Objectives

The overall objective of this research project was to update the friction evaluation portion of MD SHA's aggregate specifications. This includes:

1. Evaluation of relationships between physical, petrographic, and engineering property data for Maryland aggregate sources.
2. Recommendations for an annual aggregate test regimen that would quantify high friction, wear resistant aggregates for use on major highways and/or high accident locations, including equipment and specifications.
3. Evaluate the short and long term impact of the proposed test regimen and specifications on the eligibility of existing aggregate sources.

1.3. Research Program Approach

In order to meet the objectives of this study, the Research Team undertook a two phase process.

Phase 1 involves an in-depth literature review of existing practice related to pavement friction testing, both in the laboratory and in the field. The goal of the literature review was to review existing Department of Transportation practice and to determine if there were test procedures that show promise to determine aggregate friction properties. In addition, an analysis was conducted of legacy SHA aggregate friction laboratory testing data to determine correlations of the existing test procedures to aggregate friction values. At the conclusion of phase 1, options for further evaluation were presented to SHA. As a result, a decision was made to pursue replacement of the Maryland Track with new test equipment and procedures.

Phase 2 of the project consisted of three primary tasks. These are as follow:

1. Development of a revised aggregate acceptance procedure based upon the correlations developed under phase 1.
2. Variability study and test improvement process for the British Wheel and British Pendulum Tester.
3. Procurement of the National Center for Asphalt Technology (NCAT) Polisher and Dynamic Friction Tester (DFT), evaluation of test variability, and development of test procedures and specifications.

As a result of phase 2, a draft aggregate acceptance specification has been developed, a new test procedure for British Wheel/Pendulum was developed, new polishing test equipment was procured and implemented, and new test procedures developed.

1.4. Report Organization

This report is intended to document the work performed under both Phase 1 and Phase 2 of this effort. The chapters are organized as follow:

Chapter 2: Phase 1 – Literature Review
Chapter 3: Phase 1 – Analysis of Historical Data
Chapter 4: Phase 1 – Conclusions and Path Forward
Chapter 5: Phase 2 – Development of Laboratory Screening Procedure
Chapter 6: Phase 2 – British Pendulum Improvements
Chapter 7: Phase 2 – Investigation of NCAT Polisher and DFT
Chapter 8: Conclusions and Recommendations

CHAPTER 2. PHASE 1 - LITERATURE REVIEW

2.1. Introduction

The research team performed a search of existing documentation on laboratory tests to quantify aggregate friction characteristics. Sources such as the Transportation Research Board Transportation Research Information Service (TRIS), Research in Progress (RIP) database, American Society of Civil Engineers (ASCE) web site, Google, aggregate industry web sites, and state Department of Transportation (DOT) web sites were queried, among others.

Over 140 documents were identified from this search and logged into the literature review database. The documents were subsequently prioritized according to the relevance of each document to the needs of the project. This section of the report summarizes the literature review and the recommendations resulting from this review.

2.2. Aggregate Friction Fundamentals

A HMA pavement should be designed to provide adequate resistance to sliding to permit normal vehicle turning and braking movements (Reference 1). This has been generally referred to as skid, or friction resistance. It has been accepted in the pavement engineering community that the skid resistance of an asphalt surface is impacted by both pavement surface microtexture and macrotexture. A useful graphic of overall pavement texture and definitions of texture is found in National Cooperative Highway Research Program (NCHRP) Synthesis 291, Evaluation of Pavement Friction Characteristics as shown in Figure 2-1 (Reference 2).

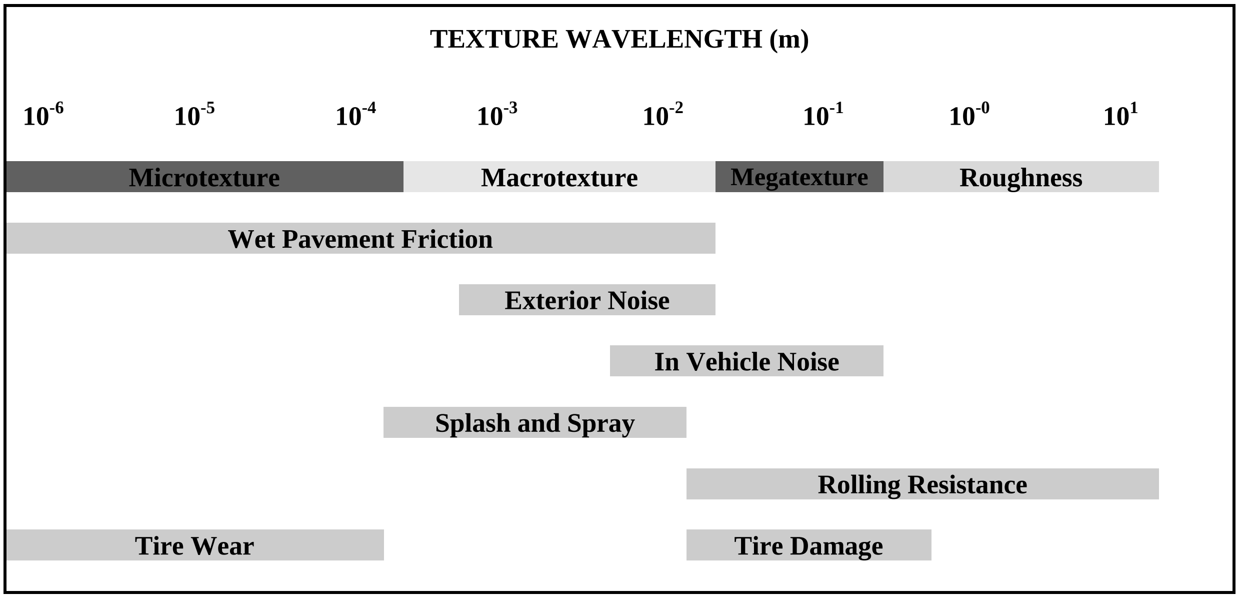

Figure 2-1. Texture wavelength effects on pavement wear

Simply stated, pavement microtexture is largely a function of the surface texture of the aggregate particles. Macrotexture is determined from the overall properties or texture of the pavement surface. Pavement macrotexture can be increased by designing pavement surfaces with greater texture depth by changing the size and distribution of sizes of the aggregates. Microtexture can only be changed by altering the types of aggregates used in the mixture.

Most states have attempted to ensure adequate friction by limiting the types of aggregates that can be used, thus controlling the microtexture. They have accomplished this by controlling the quality of the coarse aggregate (Reference 3). It is becoming increasingly difficult in many parts of the country to find quality coarse aggregates and thus transportation costs of aggregates are escalating. Also, some aggregates (such as limestone in Virginia) have been banned from use in surface courses. Aggregate suppliers have been questioning this total ban and have suggested that some limestones may be useful in asphalt pavement surface courses.

2.3. Current Practice

There has been a wide disparity in opinion within state DOTs on test procedures that should be used for determining aggregate resistance to polishing. Almost every DOT has their own method and even "standard" methods are usually modified to meet DOT needs. A few examples of current practice are described in the following sections.

Texas Tech 1996 Study

A useful study was conducted in 1996 (Reference1) to determine the current state of the practice for states to control skid resistance on HMA pavements. Because of the wide disparity in approaches, a broad categorical criterion is used to rate states' use of procedures to address skid resistance. These categories are identified in Table 2−1.

Table 2–1. Categories of procedures to address skid resistance

Category	Description
I	No specific guidelines to address skid resistance (14 states)
II	Skid resistance is accounted for through mix design (9 states)
III	General aggregate classification procedures used (7 states)
IV	Evaluate aggregate friction properties using laboratory test procedures (18 states)
V	Incorporates field performance in aggregate qualification (4 states)

In almost all cases, field skid testing is performed to determine pavement surfaces that need attention from a friction standpoint. For those states that fall into categories I (14 states) and II (9 states), they feel they have an ample supply of quality aggregates and surface friction is not a problem in their state (interestingly, Maryland was classified in category I in this study). Category III states generally limit the type and allowable percentages of a particular type of aggregate. Limestone (generally accepted as being more polish susceptible than other aggregates) has been the primary aggregate limited for use in the pavement surface course. These specifications were developed based upon the experience of the DOT with various types of aggregates and it was based upon field skid measurements. Overall, 30 of the responding states fell into category I, II, or III.

Category IV states (18 states) perform aggregate screening based upon laboratory tests. Among the laboratory procedures used, the acid insoluble residue test (ASTM D3042) and polish value test (ASTM D3319) are the two most widely used procedures. It has been noted that most DOTs modified these standard tests to meet their unique requirements. In a similar manner as Maryland, these DOTs rate aggregate sources as satisfactory based upon a series of laboratory tests. In addition to friction susceptibility tests, aggregates may also have had to pass other specifications. A useful summary of laboratory testing used by states classified as Category IV (circa 1996) is shown in Table 2−2 (Reference 1).

Table 2–2. States using laboratory testing to evaluate aggregate friction properties

STATE DOTs	Polish Value Test	Acid Insoluble Residue	Petrographic Analysis	Moh’s Hardness Number	No. of Fractured Faces	Other Test Methods
Alabama	X					
Florida		X				
Indiana						Elemental Mg Content
Iowa				X		
Kentucky		X				
Louisiana	X					
Michigan		X	X			Aggregate Wear Index
Minnesota		X				
Mississippi			X		X	
New Jersey	X					
New York		X				
Oklahoma		X				
Pennsylvania	X	X	X			
South Carolina					X	
Tennessee	X	X				
Texas	X					
Utah	X					
Wisconsin						Regression Model

As shown, various states reported using other testing procedures. One test, petrographic analysis, follows the procedures of ASTM C296-90 to identify the mineral composition of aggregates and allowed evaluation of predicted overall behavior. Another, Moh's hardness test, yields a number that identifies harder aggregates, which are considered to have better skid-resistance performance in the field. Mississippi and South Carolina reported mechanically crushing aggregates and predicting performance based on an evaluation of freshly fractured particles. Indiana's test looks for the presence of dolomite aggregates to produce skid-resistant surfaces. Michigan developed an aggregate wear index (AWI) to rate the polish resistance of aggregate samples.

Category IV states use evaluation procedures that rate the performance of HMA pavement materials in the laboratory. Only aggregates that meet established specifications during laboratory testing qualify for roadway construction use.

Category V states are trying to overcome the disconnect between laboratory screening procedures and real world friction numbers. As shown in the preceding chart, only a few states (Reference 4) were at this stage (Florida, Texas, Kentucky, and Pennsylvania). A significant problem with laboratory testing of aggregates is that laboratory test results often correlate poorly with friction performance in the field. While many states followed laboratory testing with field surveillance, Category V states used both laboratory and field test results to decide the classification of an aggregate and its appropriateness for use in new construction.

Florida, for example, reports using acid insoluble residue (AIR) laboratory testing and then building a trial pavement section using aggregates that passed AIR screening. Test methods from the ASTM E274 procedure determine the frictional characteristics of the trial section. Given satisfactory results, the aggregate has been used on a stretch of roadway with a minimum speed limit of 50 miles per hour and a traffic count of at least 14,000 vehicles per day. A control section meeting the same standards as the test section but constructed of a previously approved aggregate is connected to the test section. Crews performed field skid tests immediately, then monthly for two months, and finally every two months until six million vehicles passed or the skid resistance stabilized. When needed, an additional test section evaluated performance at 60 miles per hour. If the test section maintains skid numbers over 30 and performs as well as the control section, the aggregate receives approval for use.

Kentucky, Pennsylvania, and Texas also have comprehensive aggregate-testing procedures that combine laboratory analysis with performance history and (or) skid field tests. States found that sometimes aggregates that met laboratory specifications perform poorly in the field, while sometimes aggregates that failed laboratory test guidelines exhibit adequate performance in the field.

The authors of this study reiterated that their survey revealed state DOT procedures for evaluating skid resistance of HMA pavement materials varied from no guidelines to elaborate laboratory and field testing. An important research finding is that "**none of the state DOTs rely on skid field testing as their primary mechanism for aggregate evaluation.**"

Arguably, field testing is technically superior to laboratory testing. Why is it not the primary method used by the states? The authors offered four considerations:

1. States must collect field skid data for several years to develop a performance history that will adequately predict the success of an aggregate. Waiting for field-test results would put new or recent aggregate sources on hold for a long time.
2. Aggregates from a given source change over time, and the aggregate present in a field tested sample may not be the same as that currently available from the same source.
3. Field skid numbers are influenced by many factors such as rainfall, ambient temperatures, test speed variations, test position on the roadway, and differences in

road surfaces or in equipment operators. Different skid numbers resulting from these extraneous factors affect the reliability of test results.

4. Field testing is labor intensive and, therefore, creates heavy demands on money, personnel, and equipment.

While current practices emphasized controlling aggregate quality and, therefore, controlling the microtexture, research shows that pavement macrotexture greatly influences skid resistance. In closing, the authors describe developing technology that would allow testing of macrotexture and microtexture. Analysis of macrostructure has been difficult; however, promising methods using laser beams or a strobed band of light with high infrared content would give states the ability to gather skid resistance data using a vehicle traveling at normal highway speeds. Such developments may make analysis of macrotexture feasible and change the way state DOTs evaluate HMA pavement materials.

Louisiana 2006 Study

Another survey of the specific methods being used by the states to control skid resistance was conducted by the Louisiana Department of Transportation and Development in 2005/2006. The survey contains information from twenty-seven states and Washington D.C. Information about Pennsylvania and Alabama were obtained from other sources. Table 2−3 contains a summary of the different methods currently used by these states.

Table 2–3. Methods used to evaluate skid resistance properties

Method	Agencies
British Pendulum (BPN)	New Jersey, Alabama
Acid Insoluble Residue (AIR)	Arkansas, Oklahoma, Wyoming, Washington D.C.
Other Chemical Tests	Indiana (Soundness)
Skid Trailer	California, Florida, Georgia, Iowa, Mississippi, Montana, Nevada
Multiple Methods	Tennessee (BPN, AIR, Percent Lime, Variation of Micro-Deval)
	Texas (BPN, AIR, LA Abrasion, Soundness, Skid Trailer)
	New York (AIR, Skid Trailer)
	Pennsylvania (Petrographic, BPN, AIR)
	Virginia (Geology, Skid Trailer, Local Experience)
	West Virginia (AIR, Skid Trailer)
Other	Maryland (Test Track)
No Method – Restrictions	Delaware (Use only Maryland approved quarries)
	Kansas (Based on historical performance)
	Minnesota (No carbonate aggregate in wearing course)
No Method	Connecticut, Maine, New Hampshire, North Carolina, Oregon

Through the comparison of the 1996 survey discussed previously and this later survey, it appears to the research team that the states have not changed their aggregate friction testing programs significantly between 1996 and 2005. Many states are at the same Category level in 2006 as they were in 1996. However, a higher percentage of the states surveyed in 2006 have category 4 or 5 procedures in place (55% in 2006 versus 45% of surveyed states in 1996). Please note that these percentages are based on a survey of about half of all states wherein the 1996 survey is a complete dataset.

Also of particular significance, the only new test procedure appearing in this survey is the Tennessee T3CM procedure (using a modified version of the micro-deval device). It appears that almost all other states are using some combination of tests which have been in existence for some time. Overall, it is concluded that the state of the practice in state DOTs has evolved incrementally over the past ten years and very little innovation is occurring to develop new test procedures.

From a further review of this information, it appears that a few states seem to be taking the lead in developing robust aggregate friction testing programs. These are Indiana, Iowa, Kentucky, New York, Pennsylvania, and Texas.

FHWA Technical Advisory

FHWA Technical Advisory T 5040.36, ***Surface Texture for Asphalt and Concrete Pavements***, (June 17, 2005) contains several general recommendations for ensuring proper surface characteristics for HMA pavements (Reference 5). These are as follow:

Aggregate angularity. Frictional resistance of the wearing course is improved when angular aggregates are used in the HMA mixture. Increasing fractured faces of the coarse aggregate (reducing or eliminating rounded gravels) will improve stability of the HMA mix. Coarse aggregate angularity is defined as the percent by weight of aggregates larger than 4.75 mm with one or more fractured faces. Similar to coarse aggregates, performance is also related to the angularity of fine aggregates. It is recommended that the aggregate meet the requirements specified in AASHTO specification M323.

Aggregate soundness. Soundness is an indication of an aggregate's resistance to weathering. It is recommended that sodium or magnesium sulfate tests use the limits described in the American Association of State Highway and Transportation Officials (AASHTO) specification M29. The recommended range for sodium sulfate soundness is 12-15% maximum and for magnesium sulfate soundness is 15-20% maximum for 5 cycles. Other methods may be used to characterize aggregate soundness.

Aggregate toughness. Toughness is an indication of an aggregate's resistance to abrasion and degradation during handling, construction, and in-service. It is recommended that specifications require toughness tests and tests should be performed in accordance with AASHTO specification T96. The recommended specification value for a Los Angeles abrasion loss ranges from 35 to 45 percent maximum. (Consideration should also be given to utilizing the Micro-Deval Abrasion Test (AASHTO specification TP58)).

Polish resistance. The use of aggregates that polish easily should be avoided. It is recommended that polishing resistance of aggregates be measured in the laboratory, prior to use. An appropriate test and value for the specific pavement should be established. A set of tests for evaluating aggregate polish value is Accelerated Polishing of Aggregates Using the British Wheel (AASHTO specification T-279) and Surface Frictional Properties Using the British Pendulum Tester (AASHTO specification T-278). AASHTO specification T-278 may also be used to evaluate the polishing condition (BPN) of pavement surfaces. Other methods may be used to characterize polish-resistance of aggregates.

The contents of this technical advisory are considered important as they contain guidance as to the testing program that should be undertaken to ensure reliable, polish resistant aggregates have been used in HMA surface mixtures.

European Perspective

The European Union (EU) has seen drastic change in the last few years in terms of aggregate testing. January 1, 2004 brought the adoption of standardized test methods to every country belonging to the EU. The EU evaluated all current specifications present in member countries prior to selecting the standardized test methods. The methods chosen by the EU for aggregate testing are as presented in Table 2−4.

Table 2–4. Methods used by the European Union for aggregate testing

Physical Properties	**Test Method**
Grading	Sieve analysis
Fines content	Wet sieving to determine % <0.063
Shape	Flakiness index
Resistance to fragmentation	LA Abrasion test (reference) German Schlagversuch impact test
Resistance to wear	French Micro-deval coefficient
Resistance to polishing	British polish stone value
Resistance to surface abrasion	British aggregate abrasion value
Durability in terms of freeze-thaw resistance	Water absorption as a screening test for freeze/thaw resistance. Freeze-thaw test or magnesium sulfate soundness where necessary
Bulk density	Bulk density
Thermal shock	Sonnebrand test – 36 hour boiling in water Soaked, surface-dry aggregate heated at 70°C for 3 minutes

The authors note that the methods selected are NOT the result of a research project to develop improved predictive test methods. Rather they were existing test methods, used for years. They state specifically that there is no guarantee that the prediction of in-service performance or reduced risk will result from these procedures.

It should also be noted that there are no innovations in the European approach. The test procedures adopted by the EU, for the most part, are presently in use in the United States and there does not seem to be a difference between US and EU specifications. However, this list does illustrate the tests that the EU believed adequate to quantify the suitability of aggregates in HMA pavements.

2.4. Test Procedures

There are three broad categories of standard laboratory tests that are commonly used to evaluate the frictional properties of aggregates: mechanical, chemical, and petrological. They are discussed below.

Mechanical Tests

Mechanical tests provide a measure of the physical properties of the aggregates. The British Polishing Wheel and the British Pendulum are the most commonly used mechanical tests to evaluate the frictional properties of aggregates. It provides the Polished Stone Value, which is a measure of the resistance of the aggregate to the polishing action of vehicle tires. The test is performed in accordance with the specifications in ASTM E303-93 (2003), *Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester.*

Current mechanical testing procedures in use are as follow:

- Accelerated Polishing of Aggregates and Mixes
    - Accelerated Polishing Machine (APM) and the British Portable Tester (BPT): ASTM D3319 and ASTM E303
    - Polished Stone Value (PSV): The British Standard since 1960 and recently became the Euro Norm for measuring Aggregate Skid Resistance.
    - Micro-Deval Test (French Origin)
    - Micro-Deval Voids at 9-Hours (MDV9)
    - Circular Track Wear Method: Michigan Wear Track and Maryland Track
    - Penn State Reciprocating Polishing Machine. (ASTM specification discontinued in 1997)
    - Jar Mill Wear Method
    - Nordic Ball Mill method
    - NCSU Polishing Machine (ASTM E660)
    - NCAT Polishing Machine
    - LA Abrasion (AASHTO T96)

- Evaluation of Surface Friction
    - Michigan Laboratory Friction Tester
    - Dynamic Friction Tester (ASTM E 1911-98)
    - PTI Friction Tester (no longer used)
    - Tennessee Textural Retention Method (TTRM)
    - The Tennessee Terminal Textural Condition Method (T^3CM). The Tennessee Terminal Textural Condition Method (T^3CM) Voids device is based on a modification of the AASHTO T 304 - Uncompacted Voids Apparatus for Fine Aggregate

  - North Carolina Variable Speed Friction Tester (ASTM E707)
  - Circular Texture Meter (ASTM E2157)

Chemical Analysis

These tests use chemical means to provide a measure of the aggregate friction. Acid Insoluble Residue (AIR) is a widely used chemical test. The aim of this test is to determine the percentage and size distribution of noncarbonate material in carbonate aggregates. The theory is based on the concept that the skid resistance of carbonate aggregates is related to the differential hardness of the minerals that constitute the aggregate. When a carbonate aggregate is subjected to polish the softer minerals will wear away at a faster rate than the harder particles and there will be some attrition of the aggregate caused by the loss of the softer particles. This attrition will result in a rough texture for the aggregate surface, which will increase or maintain the friction properties. The percentage and gradation of the noncarbonate material provides a measure of the aggregate friction.

Current chemical test procedures in use are as follow:

- Percent AIR Test
- Soundness Test (ASTM C88-90): used by Ohio DOT; Texas used 5-cycle Magnesium Sulfate Soundness Test; aggregate with good polish number bears a lower soundness loss value and vice-versa.
- Percent Silica (ASTM C 25)
- Percent Silica by X-ray Diffraction.
- Loss-On-Ignition (LOI) Method (Tennessee DOT)

Petrographic Analysis

Petrographic analysis involves the examination of the aggregate to determine the physical and chemical characteristics that affect the frictional properties. The grain size and shape affect the aggregate friction. Angular grains generally tend to produce a rough texture as compared to aggregates with a smoother grain. Larger and harder grains also provide better friction. The petrographic examination is performed by a qualified petrographer generally using optical microscopy. Additional procedures such as X-ray diffraction analysis, differential thermal analysis, infrared sprectroscopy, or electron microscopy may be used.

Field Friction Testing

Field skid tests currently in use include the following:

- Locked-Wheel Trailer Methods (ASTM E249 and ASTM E274)
- Automobile Methods (ASTM E445/E445 M)
- Portable Field Devices
  - British Pendulum Tester (ASTM E303)
  - Dynamic Friction Tester (ASTM E1911)
  - North Carolina Variable Speed Friction Tester (ASTM E707)
  - PTI Friction Tester

Pros and Cons of Various Procedures

From the state of the practice review, strengths and weaknesses of several of these procedures are discussed below.

1. The BPN9 uses a British Polishing Wheel (ASTM D3319) and the British Pendulum Tester (ASTM E303)
   - The British Pendulum Tester's main problem is an extensive and ineffective calibration procedure.
   - The British Pendulum Number (BPN) after 9 hours of polishing is normally assumed to be the terminal polishing value for the aggregate.
   - Polish number is affected by the aggregate selection technique.
   - The effect of additional time and polishing media has a significant effect adding to the uncertainty of prediction.

2. The Percent Insoluble Residue Test: Should be used as a laboratory evaluation test, but not considered as a principal means of predicting skid resistance.

   - Silicates are insoluble in Hydrochloric Acid and contribute to skid resistance due to hardness of the particles.
   - Loss-On-Ignition (LOI) is superior to AIR test due to a larger sample size and an easier operation.
   - Problem with LOI test is that there is no measurement of how the harder particles of the aggregate are dispersed.
   - AIR and LOI tend to reflect the general trend of later polishing values, but polishing values could not be statistically predicted from these tests.

3. The Micro-Deval Test has issues in that the value obtained from the test is a loss value. Loss is not indicative of skid performance because some slags and sandstones have a high percent loss but have good skid resistance. Also, there is a possibility that the steel balls

would add impact to the aggregate particles creating an impact and shearing effect that is not necessarily seen on the roadway.

4. TTRM
   - Problem: cannot reveal an aggregate's terminal texture.
   - Reasons for NOT having aggregate's terminal texture were:
     - Aging was only carried out to 1200 revolutions.
     - Steel spheres introduced an impact component to the aging, thus fracturing aggregate particles. The introduction of fractured faces obscured the aggregate's terminal texture.
   - Repeatable, not operator sensitive, and inexpensive.

5. T^3CM appears to be superior to BPN, Percent Silica and LOI since to date it has not produced a false positive result, it is more repeatable, not operator sensitive, provides increased productivity, is easy to perform, and inexpensive (compared to British Wheel and British Pendulum). T^3CM has the ability to identify aggregates which will perform well in limited ADT applications and has a potential to reduce the cost of surface aggregate while maintaining a high level of safety for the motoring public. This test method appears to be a conservative, reliable surface aggregate pre-qualification method. It measures what is really important in selecting bituminous surface aggregate, the aggregate's terminal textural condition. T^3CM is labor intensive compared to MDV9 and measures only the aggregate polish resistance, a multitude of other factors also effect the skid number.

6. The MDV9 appears to be a quicker, easier T^3CM test, and has a definitive stopping point. The MDV9 is not statistically significantly different from the T^3CM at the 95% confidence interval. The MDV9 had a coefficient of variation less than 0.5% in a thirty replicate test on a Tennessee proven-performing limestone aggregate.

7. Research showed that the Standard PSV test should not be considered as a measure of an ultimate state of polish, nor should it be the sole basis of surfacing aggregate selection.

2.5. Summary

Based on the desired and stated needs of MD SHA, the following comments summarize what was learned from the state of the practice review versus MD SHA needs.

- Currently Maryland is classified as a leading state (Category 4 of 5 from state review) in terms of aggregate friction testing. Maryland takes a relatively proactive approach to classifying aggregates for friction characteristics.
- Only one other state, Michigan, appears to have a similar wearing track. This means that it is unlikely that the procedure will become an ASTM/AASHTO standard and, subsequently, multi-laboratory precision and bias cannot be assessed. Thus, use of this machine will not allow the aggregate industry to pursue a refereed test or be able to replicate state results.

- Maryland's current procedures use most of the test methods recommended in the literature to identify aggregate frictional performance (BPN, petrography, chemical analysis, soundness, etc.).
- There is no existing test or "magic bullet" to meet the state's requirement. None of the literature identifies a particular test, or series of tests, that can adequately or definitively predict pavement frictional performance based upon aggregate quality. It does not appear that any state or national institution is pursuing such a test in the near future.
- The only apparent test procedure which is not being used by Maryland that may improve test results is the micro-deval test apparatus, however, there is no conclusive evidence, besides the work by Tennessee, that suggest the micro-deval test to be any better or worse than the British wheel. Most articles speak favorably of the micro-deval test, but there is no definitive answer to the question of one test's superiority to predict in-service friction over another.
- Many DOT's have specifications that relate aggregate polishing values to traffic levels. This allows use of more types of aggregates in the surface course thus allowing a wider use of stones than would normally not be acceptable in surface mixes.
- The literature is fairly uniform that fine aggregates do not play a large role in overall micro-texture/frictional characteristics of surface mixes.
- Threshold values for the various aggregate friction tests should be well researched and documented to real world conditions in order for the testing regime to be successful.
- Some states use a combination of laboratory tests and in-service test sections to investigate marginal aggregates.
- Indiana currently has a performance based specification that puts the onus on the aggregate producer. Aggregate producers must warranty high polish value aggregates for two years.
- Changes to the British Pendulum developed by Texas should be investigated if this test is selected as a candidate screening tool.
- The Tennessee method using the MDV9 procedure is considered a candidate for further laboratory testing due to its reported success.

The complete state of the practice review was issued to SHA on May 1, 2006. The May 2006 version contains an annotated bibliography for each piece of literature.

CHAPTER 3. PHASE 1 - ANALYSIS OF HISTORICAL DATA

3.1. Introduction

MD SHA has maintained a database of MD Track testing and aggregate properties performed between 1994 and 2005. The aggregate properties included within these data include chemical, geological, and mechanical properties for both carbonate and non-carbonate aggregates.

Two analyses were conducted using this data. The first was an evaluation of the track test results to determine if efficiencies could be gained. The second was a detailed correlation study relating aggregate properties to track and British pendulum testing to determine if chemical, geological, or mechanical properties can predict frictional resistance of aggregates.

The results of this analysis were presented to MD SHA staff and the Aggregate Industry Partnering Committee in August 2006.

3.2. Maryland Track Analysis

The MD Track data was analyzed to discern the general variability of the test procedure, identify areas of the test that could be made more efficient (if the test is continued), and identify trends in Polish Value (PV) values over time. The following analyses were performed:

- Review within test variability by comparing each of the test readings (1-4) at a pit stop to average values at each pit stop. This has been used to determine if using the average of the four readings is reasonable and to determine the variability of individual test readings.
- Determine variability of duplicate specimens within a given track series. This has been performed to determine if replicate samples produced similar results and validate the notion of using the average to determine PV. This analysis was used to make conclusions as to the variability of the coupons with respect to coupon preparation and the usefulness of using duplicate coupons.
- Review number of revolutions versus PV value to determine if reducing the number of revolutions without affecting test results is possible.
- Review each individual source PV value over time to determine if PV values are indeed decreasing as was perceived.

The MD Track data consists of the following:

- Data from 10 tracks - tracks 63 to 72
- 7 aggregate specimens tested each track
- Two specimens per aggregate
- Two control specimens, Texas and Ottowa Sand

The variability between pit stop readings analysis results in the following conclusions:

- 1408 data records
- Checked for variance of individual readings from mean
- Every reading at a pit stop was within 2 standard deviations (SD) from mean of 4 readings for that pit stop
- 66% of readings less than 1 SD from mean
- Conclusion : there are no outliers in the dataset – i.e. reasonable, repeatable data

An analysis was conducted of the variability of duplicate specimens within a given track series. The following are the results of this analysis:

- 770 records
- Control specimens excluded (there was only one specimen per track series)
- Analysis of variance performed
- Significant difference between data from duplicate specimens over entire test procedure
- For final PV, no significant difference
- Conclusion: no need for duplicate specimens if only final PV used in subsequent analysis

The effect of the number of revolutions on the PV was analyzed. The results are as follow:

- 1408 records
- Regression performed between number of revolutions and PV
- Overall results show that number of revolutions has a significant effect on PV

A secondary analysis was performed to determine if the number of revolutions could be decreased. The results are:

- Plotted average of pit stop readings against number of revolutions for 15 samples
- Fit logarithmic regression lines for each of these 15 samples
- Curves start to flatten out at approximately 1.2 million revolutions
- Performed a paired t-test for readings at 1.2 and 1.5 million revolutions
- T-test indicates difference is not significant
- Conclusion: number of revolutions can be decreased from 1.5 million to 1.2 million

The next analysis concentrated on determining if (for a given aggregate source) PV declined over the years. The results are as follow:

- 13 sources have PV data from multiple years
- ANOVA performed with source as factor and year sampled as covariate
- No significant difference of PV over time – p=0.583
- It does not appear that PV from a given source has declined over time

From the results of this analysis, the following conclusions were reached:

- The analyzed MD Track data seem reasonable and repeatable
- If only the final PV is used, there is no need to test duplicate specimens (throughput of the procedure could be doubled).
- If the test is continued, the number of revolutions could be reduced from 1.5 million to 1.2 million
- It does not appear, from the given data set, that the average PV has declined for a given source over the last few years

3.3. Correlation Study Overview

The purpose of the correlation analysis was to determine if significant relationships exist between PV and BPN values. PV and BPN values were also compared with other chemical, geological, or mechanical property test results to determine if these tests could be used as a screening tool or identifier of polish resistant aggregates. Data analyses were performed separately for carbonate stones and non-carbonate stones.

Polish Value (PV) versus British Pendulum Number (BPN)

This analysis was performed to determine if a correlation could be established between PV and BPN. Two hundred twenty five (225) test results were present that have both PV and BPN. The analysis was conducted from an individual test perspective and a time series perspective. The analysis was performed for carbonate and non-carbonate stones individually along with a combined analysis using all test results and material types.

Polish Value and British Pendulum Number versus Other Test Results

For carbonate stones, the analysis was conducted at the following three levels:

1. General - at this level, general relationships between PV/BPN values and other testing results were examined, regardless of material type and material source.

The following relationships were examined:

a. Correlation between Total Insoluble Residue and PV/BPN
b. Correlation between LA Abrasion and PV/BPN
c. Correlation between Micro-Deval and PV/BPN

   d. Correlation between Sodium Sulfate and PV/BPN
   e. Correlation between Sieve Gradation and PV/BPN
   f. Any combining effects of BPN, Total Insoluble Residue, Sieve Gradation, LA Abrasion, Micro Duval, Sodium Sulfate, on PV values

A statistical regression analysis was used to analyze the relationships.

2. Subcategory level - at this level, the effect of aggregate texture on each of above relationships was examined. The aggregate textures were grouped into 6 categories: very fine, fine, fine-medium, medium, medium-coarse, and coarse.

3. Material Source Time Series Analysis - at this level, a time series analysis was conducted to determine if PV values are changing over time for a particular source.

When insufficient data samples were available for a specific relationship, the analysis for that relationship was omitted.

Similar to carbonate stones, the analysis on non-carbonate stones was also conducted at the same three levels. They are:

4. General Level - at this level, general relationships between PV/BPN values and the other test results were examined, regardless of material types and material sources.

   a. Correlation between LA Abrasion and PV/BPN
   b. Correlation between Micro-Deval and PV/BPN
   c. Correlation between Sodium Sulfate and PV/BPN
   d. Correlation between ASR and PV/BPN
   e. Any combining effects of BPN, LA Abrasion, Micro-Deval, Sodium Sulfate, on PV values

A statistical regression analysis was used to build these relationships.

1. Subcategory Level - at this level, the effect of rock categories on each of above relationships were examined. The non-carbonate stones were grouped into the following categories: Greenstone, Diabase, Serpentinite, Granite Clan, Hornfets, Sandstone, Silicon Dioxide, Aluminia, Quartz, and Feldspar.

2. Material Source Time Series Analysis - at this level, a time series analysis was conducted to determine if PV values were changing over time for a particular source.

Carbonate Aggregates Data Analysis

For carbonate aggregates, the following data elements were studied:

- Polish Value
- British Pendulum Number
- Percent Total Insoluble Residue
- Percent +200 Mesh Insoluble Residue
- LA Abrasion (Percent of Loss)
- Micro-Deval Loss
- Sodium Sulfate (Percent of Loss)
- Gradation of +200 Mesh Portion

General Analysis

The data were analyzed using a linear regression approach. The correlation coefficient, r, is used to determine the correlation between the two data sets. A correlation coefficient greater than zero (r scale ranges from -1 to +1) generally means there is a correlation between two sets of data. A r-value greater than 0.8 generally indicates a strong correlation. A correlation coefficient less than 0.5 is generally considered a weak correlation.

As shown in Table 3-1, the PV and BPN have a strong correlation and both the PV and BPN have a strong correlation to the total insoluble residue test.

Subcategory Level

At the subcategory level, the effect of aggregate texture was investigated. This analysis includes aggregate textures grouped into 6 categories: very fine, fine, fine-medium, medium, medium-coarse, and coarse. For this case, the medium-coarse category only has 2 records and was excluded from the analysis. Based on a multiple regression analysis, models for very fine, fine, medium, and coarse have high significance with respect to PV and BPN test results. Thus, texture plays a role in aggregate friction for these textures.

Material Source Time Series Analysis

In this analysis, the research team was trying to determine if carbonate aggregates from a particular source were changing (given PV test results) over time. For this analysis 31 sources have PV data from multiple years. Based on an Analysis of Variance (ANOVA) with source as the factor and year of test as a covariate, there is no significant difference in PV within a source over time.

Table 3–1. Summary of general analysis of carbonate aggregates

Correlation		# Data Points	Correlation Coefficient	Correlation
PV	BPN	121	r=0.850, p=0	Strong
	Total Insoluble Residue	110	r=0.825, p=0	Strong
	LA Abrasion	122	r=0.040, p=0.666	Weak
	Micro-Deval	18	r=0.358, p=0.144	Weak
	Sodium Sulfate Soundness	122	r=0.070, p=0.444	Weak
	#4 Sieve	102	r=0.040, p=0.666	Weak
	#4-#8 Sieve	106	r=0.040, p=0.666	Weak
	#8-#16 Sieves	106	r=0.188, p=0.054	Weak
	#16-#50 Sieves	107	r=0.023, p=0.815	Weak
	#50-#200	107	r=0.002, p=0.98	Weak
BPN	Total Insoluble Residue	110	r=0.808, p=0	Strong
	LA Abrasion	122	r=0.136, p=0.138	Weak
	Micro-Deval	18	r=0.495, p=0.037	Weak
	Sodium Sulfate Soundness	122	r=0.033, p=0.716	Weak
	#4 Sieve	102	r=0.136, p=0.138	Weak
	#4-#8 Sieve	106	r=0136, p=0.138	Weak
	#8-#16 Sieves	106	r=0.111, p=0.258	Weak
	#16-#50 Sieves	107	r=0.003, p=0.976	Weak
	#50-#200	107	r=0.083, p=0.397	Weak

Non-Carbonate Aggregate Data Analysis

For non-carbonate aggregates, the following data elements were studied:

- Polish Value
- British Pendulum Number
- LA Abrasion
- Micro-Deval
- Sodium Sulfate Soundness

General Analysis

As with the carbonate rock, data were analyzed using a linear regression approach. The correlation coefficient, r, was used to determine the correlation between the two data sets. A correlation coefficient greater than 0.8 generally is a strong correlation. A correlation coefficient less than 0.5 is generally considered a weak correlation.

As shown in Table 3−2, the PV and BPN have a relatively weak correlation, although the “p” statistic equals zero, indicating there is a correlation. Likewise, PV has a relatively weak correlation to LA Abrasion but the “p” statistic is zero. All other comparisons have a very weak correlation.

Table 3–2. Summary of general analysis of non-carbonate aggregates

Correlation		# Data Points	Correlation Coefficient	Correlation
PV	BPN	104	r=0.437, p=0	Weak, p=0
	LA Abrasion	104	r=0.385, p=0	Weak, p=0
	Micro-Deval	20	r=0.178, p=0.452	Weak
	Sodium Sulfate Soundness	104	r=0.150, p=0.135	Weak
BPN	LA Abrasion	104	r=0.058, p=0.56	Weak
	Micro-Deval	20	r=0.096, p=0.686	Weak
	Sodium Sulfate Soundness	122	r=0.022, p=0.828	Weak

Subcategory Level

At the subcategory level, the effect of aggregate type was investigated. This includes Greenstone Diabase, Serpentinite, Granite Clan, Hornfels, Sandstone, Quartz, Basalt, Gneiss, Quartz, Diorite, Schists. The Diorite, Schist, and Quartz were excluded as only 3 records exist for each of these categories.

From a multiple regression of each individual factor, LA Abrasion and BPN are the factors that have significant correlation with PV. In addition, a multiple regression was carried out for each aggregate type with the above factors. The analysis resulted in a finding that aggregate type could not be correlated with PV.

Material Source Time Series Analysis

In this analysis, the research team evaluated whether or not non-carbonate aggregates from a particular source were changing (given PV test results) over time. For this analysis 6 sources have PV data from multiple years. Based on an Analysis of Variance (ANOVA) with source as the factor and year of test as a covariate, it was found that five of the six sources show a decrease in PV over time.

3.4. Conclusions

The following conclusions are drawn from the analysis of carbonate aggregates:

- A good correlation is observed between PV and BPN.
- Total Insoluble Residue and BPN are significant factors affecting PV.
- Aggregate textures of coarse, medium, fine, and very fine have a significant effect on PV. Fine-medium and medium-coarse textures did not significantly affect PV.
- Data source does not have a significant effect on PV for the carbonate aggregates evaluated.

The following conclusions are drawn from the analysis of non-carbonate aggregates:

- Though not as strong as for carbonate aggregates, PV and BPN have a significant relationship.
- LA Abrasion is a significant factor affecting PV.
- Aggregate type has no significant effect on PV.

These results were used in development of an aggregate screening procedure in Phase 2 of the study.

CHAPTER 4. PHASE 1 - CONCLUSIONS AND PATH FORWARD

4.1. Introduction

Phase 1 work activities included a review of the current state of the practice in aggregate friction and an analysis of the MD SHA aggregate friction database. Some of the conclusions reached in phase 1 are as follows:

- There is no proven laboratory test used by a state DOT that can predict aggregate friction field performance with a high degree of certainty.
- Some states use a mix of test procedures to qualify their aggregates as high polish. A few rely entirely on field performance.
- Through data analysis, the MD Track has been verified to be measuring a form of polishing of the aggregate but this has not been correlated to field friction measurements.
- The Maryland Track test procedure correlates moderately well with results from the British Pendulum test.
- Other tests (Total Insoluble Residue and LA Abrasion) have been statistically correlated with both the PV (MD Track) and to some extent the British Pendulum results.

Based on these results, the research team has outlined ten potential options for further consideration by MD SHA to determine coarse aggregate frictional properties. A description of each alternative was presented along with an estimated cost to implement each alternative. Pros and cons associated with each option were also presented.

4.2. Options

Ten options were evaluated by the team. The options presented are as follow:

1. Do nothing, keep testing regime as it is,
2. Update and modernize the MD Track,
3. Option 1 or 2 with modified MD Track testing procedure,
4. Option 1 or 2 but use the British Pendulum to measure aggregate friction,
5. Replace MD Track with British Wheel and British Pendulum,
6. Replace MD Track with NCAT Polisher and British Pendulum,
7. Replace or supplement Options 1-6 with field evaluation method,
8. Replace or supplement Options 1-7 with laboratory testing flagging procedure,
9. Replace all laboratory testing with field warranty specification,
10. Develop new laboratory test procedure that correlates with field performance values.

Highlights of each option (repeated verbatim from the source report) are discussed in the following sections.

Option 1 – Do Nothing

This option entails moving the MD Track to Hanover, calibrating the equipment, and resuming the testing process as it currently exists. The data analysis conducted verifies that the MD Track procedure does show a decrease in friction values over the test regime and is repeatable between duplicate specimens. The data analysis confirms many of the results obtained during the original development of the procedure in the 1970's. The MD Track procedure is one of the more pragmatic aggregate friction acceptance procedures in the United States as it closely simulates traffic loading and wear over time and it attempts to simulate the field friction measurement process.

The cost to pursue this option (also referred to as the base case), is zero. It is assumed that the budget for moving the device has already been programmed into the move to Hanover. All other option costs are referenced against this zero cost base case.

The primary argument for this option (pro) is that the MD Track has a long and consistent history in the State of Maryland and a substantial database has been developed of test values by source and time. However, this procedure takes a great deal of time to conduct and its results cannot be replicated by other parties. Also, it is still unknown if this test procedure correlates well to field friction performance of the HMA mixture. Based on a preliminary data analysis conducted by MD SHA on a small data set, and because the procedure tests coarse aggregate only, there are serious doubts that the MD Track will relate well to in-service field friction values which contain the additional influences of field test variability, fine aggregate, and asphalt binder. Additional cons related to this procedure are that the precision and bias of the test procedure is difficult to determine (thus one never knows what the error of the procedure is) using one set of test equipment, the test has a very long test duration and thus limited throughput for a given year, and producers or other stakeholders cannot independently verify the test results.

Option 2 – Update and Modernize MD Track

This option entails moving the MD Track to Hanover and continuing its use albeit with a complete modernization effort. The exact scope of the modernization is to be determined by an in-depth study but it could entail reengineering the torque measurement system, development and implementation of new measurement transducers, signal conditioning, and data acquisition systems as well as upgraded software to control, monitor, and analyze test results. A review of the sample preparation procedure would also be conducted under this option in order to automate the process and produce consistent coupons.

The cost to pursue this option is dependent on the results of the functional analysis that will need to be conducted to determine the extent of the upgrades. However, it is estimated that this task will require between $100-150k, with roughly half that effort involving professional services to evaluate and then design, program, and implement the new system.

Selection of this alternative would have benefits such as improving the accuracy of the test procedure, automation of data capture and analysis, and maintaining consistency (historical traceability) with the existing procedure. Some of the fundamental issues with the test procedure would not be resolved such as the length of time to conduct the test, lack of reference testing by producers (producers cannot replicate the test), and the fact that the precision and bias of the procedure is difficult to determine using one set of test equipment. Also, the correlation to field test values and field performance is still unknown with this test procedure.

Option 3 – Option 1 or 2 with Modified MD Track

Option 3 entails simply utilizing the results of the data analysis conducted previously to shorten the test duration and use only one test coupon. The data analysis indicated that using 1.2 million revolutions is adequate to determine the final PV. Also duplicate specimen results indicate that only one specimen is needed to determine the test result.

This option could be used with options 1 or 2 to improve the existing test procedure. The same costs and pros and cons would exist as per the previous two options ($0-150k dependent on option selected). This option would yield a two week savings in test duration and double throughput as duplicate specimens will no longer be needed. A potential con with this option is that sample variability cannot be determined using only one sample.

Option 4 – Option 1 or 2 with British Pendulum

This option entails using the MD Track to polish specimens and utilization of the British Pendulum to determine the PSV. In order to implement this option, the same decisions will need to be made regarding upgrading the existing system. However, with this option substantial upgrades to the electronics and data analysis system do not need to be made. Modifications to the coupon bracket may need to be made to allow placement of the British Pendulum consistently. Option 3 also may be implemented with this option.

The costs to implement this option are relatively minor (<$50k) and primarily involve development of an enhanced coupon compaction system to achieve increased uniformity between samples and a study to decrease the variability of the British Pendulum test.

The pros associated with this option include decreased variability of the procedure due to measurement of the PSV on the same spot of the coupon for every measurement, the ability to conduct British Pendulum testing on both lab and field samples so that correlations may be made, and a decrease in the complexity of the friction measurements. The cons include the need to decrease the reported variability of the British Pendulum test, MD SHA will lose the link with historical aggregate friction tests, producers still cannot replicate the test results and the polishing portion of the procedure still has a long test duration. Also, the link between laboratory and field values is still not proven with this test procedure.

Option 5 – Replace MD Track with British Wheel/British Pendulum

The previous data analysis effort established a promising correlation between the existing track and the British Wheel/Pendulum test procedure. This option therefore considers replacement of the MD Track with the British Wheel and Pendulum test.

The costs to implement this option would be relatively small (<$50k) with the primary effort being to reduce the variability of the British Pendulum test and establish correlation with potential producer equipment.

This option carries substantial benefits to the MD SHA and producer groups. First of all, the equipment already exists within MD SHA and is used on a consistent basis. It will allow direct correlation and companion testing between the two groups, and allow substantially increased throughput and frequency of testing. This test is an industry standard that is accepted throughout most of the world as an adequate predictor of aggregate frictional properties. However, we have learned through the literature review that there is very limited correlation of this data with field frictional values. The test also has been shown to be highly variable and many tests are needed on a particular specimen to ascertain the final number. A research study should be undertaken to reduce the variability in a similar manner as has been undertaken in Texas. MD SHA would also lose the historical history that has been accumulated with the MD Track procedure.

Option 6 – Replace MD Track with NCAT Polisher/British Pendulum

The National Center for Asphalt Technology (NCAT) polisher has shown promising results in research conducted by the Indiana and Ohio DOTs. The machine performs in a similar manner as the MD Track but rotates at a much higher frequency and thus polishes the material much faster. It has a smaller footprint than the MD Track but is still not bench-sized – a fairly large area is needed to conduct the test. Also, this device has not been used with coupons so a coupon mounting system needs to be created. The NCAT Polisher also only polishes the specimens; a device is needed to measure the PV of the specimens. For this option, the British Pendulum device is considered a suitable test procedure.

The costs to implement this option are estimated to be $100-$150k. While the NCAT polisher is relatively inexpensive (estimated to be $10k by Indiana), there are substantial costs associated with developing the system to test aggregate coupons. A mounting system must be designed, tested and implemented and a variability study conducted to determine the accuracy of the test procedure. And again, a link to field test results is deemed imperative to determining the predicative capability of the test procedure with in-service conditions. There are many risks associated with this alternative.

This option yields improvements to test duration and throughput and theoretically it could be procured by the producers and used by them to verify test results. However, the producers still need to make a substantial investment. This test procedure potentially could have a large learning curve as mentioned in the previous paragraph. The NCAT Polisher is a custom designed machine and therefore each device would need to be made from scratch – there are no suppliers for the system at this time. However the same machine shop used to develop Indiana's device could be used to develop any new systems. In addition, this system has only been used to test asphalt coupons. Its use with aggregate specimens is not known. A fair bit of research and development may be needed to determine the number of revolutions and test duration with this device. The issues with the British Pendulum would also need to be overcome as mentioned in previous options.

Option 7 – Replace/Supplement Options 1-6 with Field Evaluation Methodology

This option considers a rather new approach. Option 7 contemplates combining one of the previous options and developing a field evaluation option to supplement the laboratory evaluation methodologies. This option would include establishing a robust database of aggregate source materials (potentially through the Materials Management System) that have been approved for high polish value pavements, and use of the yearly pavement friction evaluation program data to correlate the data. This will allow monitoring of aggregate sources using realistic data. If designated high-polish aggregates perform well in the field then perhaps source testing could be reduced. If designated aggregates perform poorly, a more in-depth evaluation of aggregate data could be performed and increased testing performed.

The costs to perform this option are estimated at $100k. This would primarily involve development of a database to link the laboratory aggregate data with sources and development of an evaluation algorithm and testing of the algorithm over a large dataset.

This option has the benefit of establishing a potential strong link between laboratory testing and field performance. However, there may be a long period of trial and error before the procedure is accepted by MD SHA and industry and it may take a long time for field data evaluation to occur. Also, the severe confounding effects of asphalt production, compaction, aggregate orientation, and influence of fine aggregates and binder (among other things) may be too large to adequately predict field performance from laboratory testing. Most of the research reviewed during the literature search concluded that this relationship (coarse aggregate to HMA) is difficult to determine due to the confounding effects noted. It also may be difficult for producers to screen aggregates.

Option 8 – Supplement Options 1-6 with Laboratory Flagging Procedure

For all options under consideration, the data analysis conducted previously has found that there are significant correlations as follow:

1. Carbonate: PV to BPN, Total Insoluble Residue to PV and BPN, Aggregate Texture to PV/BPN
2. Non-carbonate: PV to BPN, LA Abrasion to PV

Based on this analysis, it is possible that options 1-7 could be supplemented with these test values and correlations to screen aggregates for polish susceptibility and monitor aggregate quality over time.

The costs to implement this option are considered to be zero as the tests are already conducted and no additional investment will be needed. In fact, the BPN and Total Insoluble Residue tests are currently run as part of the high polish value acceptance procedure. It is possible that a focused research study may need to be undertaken to enhance the correlation results based on a larger dataset but that decision would need to be made at a later date. For the purposes of this discussion, the current dataset is deemed to be robust enough to adequately model and develop the correlations between the test results and PV values.

The primary advantage of this option is that relatively simple and short duration laboratory tests can be run to screen aggregates for high polish. These tests are easily replicated by industry and are industry standards. Use of surrogate test results for aggregate screening are currently a part of the MD SHA acceptance procedure therefore new development work will be kept to a minimum. There are no obvious disadvantages to this option except perhaps that the link between these tests and aggregate field performance is not established.

Option 9 – Develop Warranty Specifications

This option would entail development of a warranty specification that requires a certain guaranteed performance on the as-placed HMA. This type of end-result specification is gaining increased traction in DOTs across the country but is only used in Indiana on a regular basis (for aggregate friction performance acceptance) at this point in time (2006).

The costs to implement this option are estimated to be approximately $200k. The primary effort will be professional services to develop the warranty specification and field testing to determine the practicality of this option.

This option shifts the risk entirely to the aggregate producer community and its adoption would be very difficult considering the many players involved in placing and warranting the placed asphalt. Ultimately this risk may fall on the bonding industry which insures contractors. This industry is somewhat risk averse and it may not allow insurance of this particular performance measure without widespread implementation as a risk profile is not available with which to make bonding decisions. This option could also ultimately result in significant increases in aggregate costs (to factor in risks) that may make the option impractical. These issues would need to be investigated prior to adoption.

Option 10 – Develop New Procedure

The final option considered is development of an entirely new test procedure to definitively link laboratory test results to field performance. Alternatives to conduct this option are almost limitless. The literature review did not find a test procedure that was conclusively determined to reach this goal. Development of such a test would require intensive research, development and implementation costs estimated at between $500-1,000k. As a case in point, NCHRP has recently spent well over $1,000,000 the past five years to develop a suite of aggregate performance tests and not one of the studies developed a suitable procedure to predict aggregate friction.

It is theorized that this option would primarily be concerned with testing asphalt specimens containing the aggregate under study and an in-service investigation to relate the laboratory test results to field performance. Indiana is conducting such a study with limited success to-date.

4.3. The Path Forward

A series of meetings were held in November and December 2006 to discuss these options and determine a path forward. As a result of these meetings, which included MD SHA, aggregate industry participants, and the project team, three study tracks were developed for Phase 2 of the project. These are:

Track 1. Development of a method to determine when a source aggregate has changed geology (petrography based) and development of a laboratory testing regime to screen aggregates for polish susceptibility and monitor aggregate quality over time (Option 8).

Track 2. Investigation of the British Wheel and Pendulum to perform friction acceptance (Option 5).

Track 3. Investigation of NCAT Polisher (option 6) and Dynamic Friction Tester (DFT) to perform friction acceptance.

A significant addition to the study is the evaluation of the DFT in concert with the NCAT Polisher. A synopsis of the Phase 2 study tracks are discussed in the following sections.

Track 1 – Development of Laboratory Screening Procedure

Laboratory test screening will consider the use of surrogate laboratory tests to pre-screen aggregates and determine their potential for providing high friction characteristics. Data analysis conducted previously indicated that a few test procedures have a significant correlation to polish values and British Pendulum results. The intent of this phase of the study is to develop the models that can be used to predict aggregate friction properties and to codify these relationships in a specification. All of the considered test procedures are conducted by MD SHA so this task will be concerned with developing the correlation models to be used to perform the screening operation. This track will use the existing models developed previously, and determine a cut-off point after which an aggregate is deemed to be incapable of being classified as high-polish. Some cut-off values have already been established by MD SHA in current specifications. These will be used as the starting point and the previous data analysis consulted to determine updated models for these parameters.

Track 2 – British Wheel/Pendulum Testing Alternative

An investigation to reduce test variability and improve performance of the British Wheel and Pendulum tests will be undertaken. This may include a laboratory investigation conducted at MD SHA facilities. The end result will be a final recommendation as to the viability of this alternative to produce reasonable, repeatable aggregate friction results for use in MD SHA's specification and an improved Maryland test procedure

Track 3 – NCAT Polisher and Dynamic Friction Tester

This track will investigate use of the NCAT Polisher and the DFT as the de facto method of test for determining aggregate frictional properties. This will include procurement of a NCAT polisher and DFT and development of a testing regime to polish aggregates. This could involve a fabrication and test method development effort to adapt the polisher to Maryland requirements.

CHAPTER 5. PHASE 2 - DEVELOPMENT OF LABORATORY SCREENING PROCEDURE

5.1. Introduction

The objective of Phase 2, Track 1 of the work plan was the development of a laboratory screening procedure to monitor the consistency of aggregate source geology to determine if and when a source should be sampled for friction testing. Task 1 of this track involved a literature review to determine how petrography can be used to track a change in aggregate consistency. A report of this literature review, which determined that there is very little information on using petrography to identify change in geology, was documented in a short memorandum to SHA. Task 2 of this track involved the development of correlations between laboratory testing and the measures of aggregate friction. Task 3 was the development of a standard definition determining source consistency based on the results of Tasks 1 and 2. This section of the report presents the work undertaken to develop the draft source consistency criteria.

5.2. Development of Correlations Between Laboratory Testing and Aggregate Friction Prediction

Data analysis of the aggregate friction data has been documented previously in this report. The data received from SHA included a database containing chemical, geological, and mechanical test results and results from the MD track testing from 2002 to 2005. The data was organized based on the aggregate type: carbonate and non-carbonate. The results of this analysis indicate correlations between some of the laboratory testing and friction numbers. These correlations were further analyzed as described below.

Carbonate Aggregates

Prior data analysis indicates that the following correlations are significant for carbonate aggregate:

- PV to BPN,
- Total Insoluble Residue (TIR) to PV/BPN, and
- Aggregate Texture to PV/BPN.

Subsequently, SHA decided that it will pursue the BPN as a measure of aggregate friction. Therefore, in this analysis, only the relationships of TIR and Aggregate Texture with BPN were studied.

Since this study only considered BPN, a larger data set, which included data points that have TIR data but no PV data and were previously excluded, were used. This resulted in 137 data points compared to the 110 used in earlier analyses. With the larger data set, a significant relationship between TIR and BPN was confirmed. A linear regression model was developed between these two factors as presented in Figure 5-1.

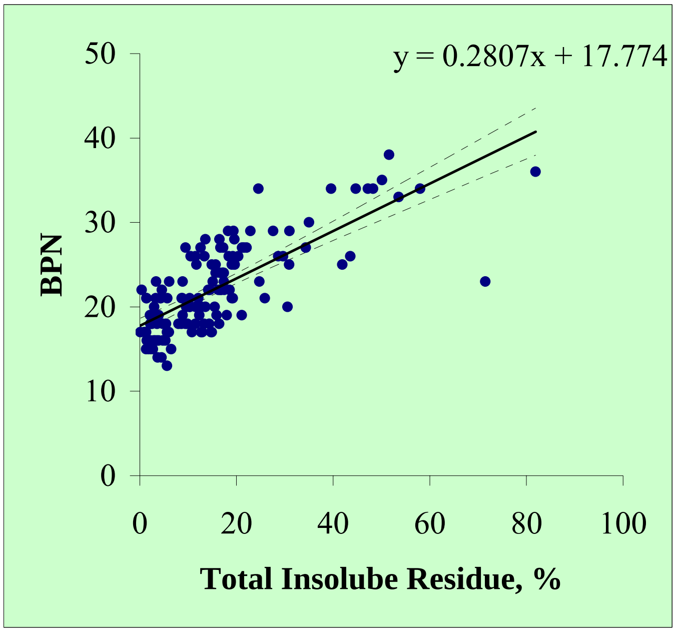

Figure 5-1. Linear regression between TIR and BPN

This linear regression model indicates that a drop of approximately 3% in the TIR will result in a decrease in the BPN of 1.

The provided dataset was categorized into six texture types: Very Fine, Fine, Fine Medium, Medium, Medium Coarse, and Coarse. In this study, for each texture multiple regressions were performed with the BPN. Aggregates with a Medium-Coarse texture were excluded since there are only three data points. As in the previous study, the regressions are significant for all textures except for Fine-Medium. This indicates that for aggregates with a Fine-Medium texture, there will not be a significant variation in BPN with variation in the TIR. However, the data points for this texture are very limited (only 8 points) which is not considered adequate to make a firm conclusion. Overall, the data indicate that results from the texture portion of the petrography examination have a bearing on the potential frictional properties of the aggregate.

Non-Carbonate Aggregates

The previous data analysis established a correlation between the results of the LA Abrasion test and the PV. While there is a significant correlation between the PV and BPN, there is no direct correlation between BPN and the LA Abrasion value. Therefore, the LA Abrasion value was not considered further as a screening tool for determining source consistency for non-carbonate aggregates.

5.3. Development of Standard Definition

The objective of this task was to develop a standard definition to determine when a source has changed its geology and to provide recommendations for sampling frequencies for friction testing. From the literature review conducted under Task 1, no standard was identified for quantifying petrography for use as an indicator of geological change. However, any change in the rock type as identified through a petrographic examination indicates a definite change in geology, which may affect aggregate friction. Also, aggregate texture is also a potential screening tool for knowing when an aggregate has potentially changed frictional properties. Another factor identified as a possible indicator of rock change necessitating friction testing, for carbonate aggregate, is the result of the Acid Insoluble Residue test. This determination is supported by the results of the data analysis undertaken in previous efforts under this study.

The current MD Track test is conducted for an aggregate source once every 3 years. With the proposed replacement of the MD Track with the NCAT polisher, the time required to polish an aggregate sample will be reduced from three months to approximately one or two days. Measuring the friction with either the BPT or the DFT is very quick, each taking just minutes to perform.

The following are the recommendations resulting from this evaluation:

1. Perform petrographic examination of the proposed high polish aggregate source on a yearly basis as a means of quantifying the type and texture of aggregate being supplied to the SHA. This will be used for monitoring and information purposes only. The important information resulting from this evaluation will be aggregate type and texture.
2. Perform AIR testing on proposed high polish carbonate aggregates as per current specifications. This data will be combined with the resultant test procedure (DFT or BPT) to develop future correlations and further refine the breakpoints between acceptable and not acceptable aggregate.
3. Perform friction testing on a yearly basis for all high PV sources. Because the proposed new procedures take a relatively short time, the new high polish test procedure should be used yearly as another classification test.

Figure 5-2 presents a flow chart of the proposed aggregate friction testing process based upon the above recommendations. The value for BPN presently in the process will be substituted for the appropriate DFT number in the future.

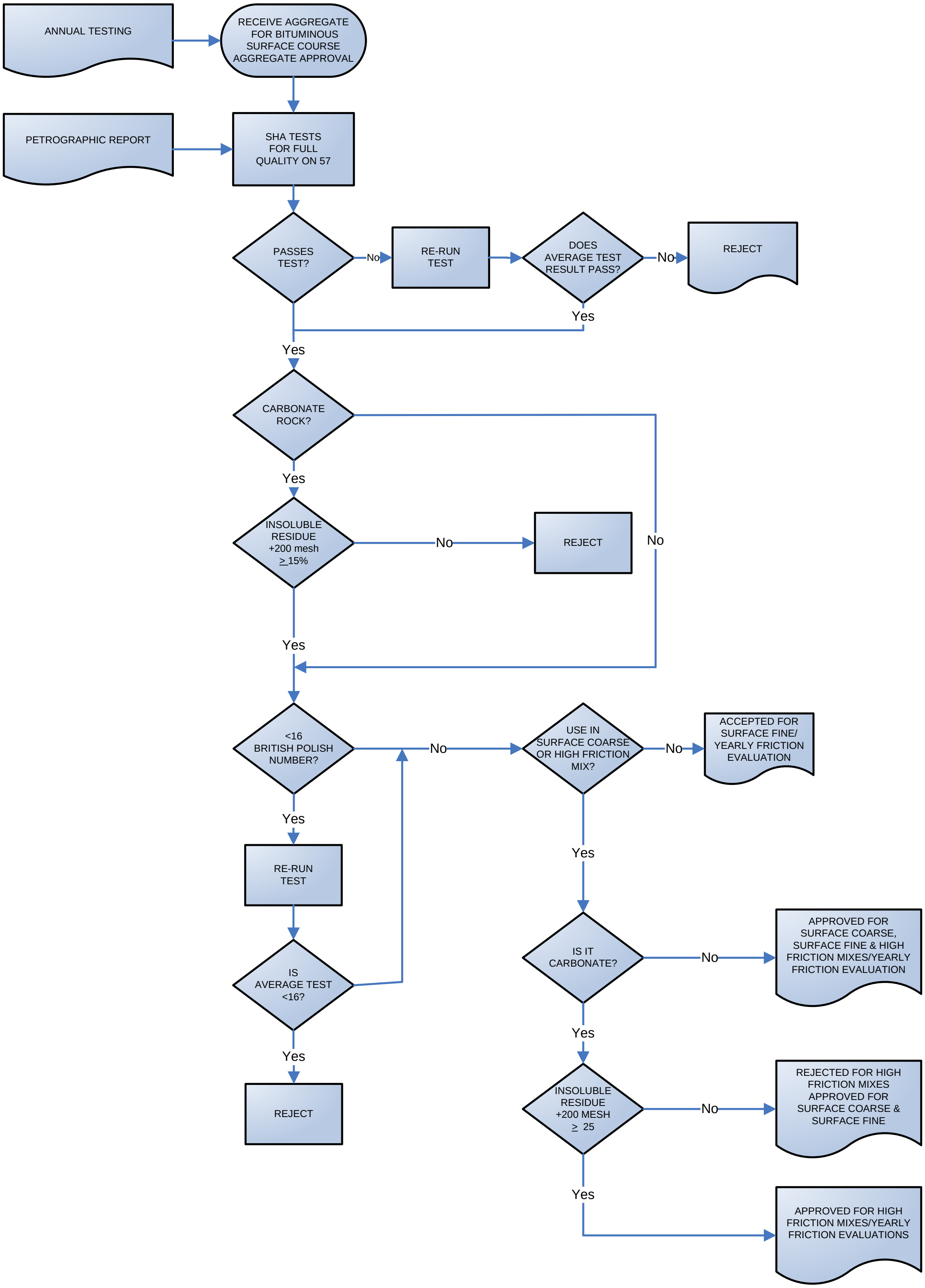

Figure 5-2. Proposed aggregate friction testing process

CHAPTER 6. PHASE 2 - BRITISH PENDULUM IMPROVEMENTS

6.1. Introduction

The British Wheel simulates the polishing action of vehicles on coarse aggregates used in HMA surface mixes. The British Pendulum Tester is a dynamic pendulum impact-type tester which measures the loss of energy when a rubber slider edge is pushed over a test surface. The tester is suited for both laboratory and field tests on flat surfaces, and for polish value measurements on curved laboratory specimens from accelerated polishing-wheel tests (i.e. British Wheel).

As part of the study to evaluate the current aggregate friction testing process used by the MD SHA, a literature review was conducted to investigate the advantages and shortcomings of using the BPT as a laboratory procedure. This review identified several advantages and several shortcomings of using the tester in this manner. A few of the advantages are that the BPT is portable, easy to handle in the laboratory as well as in the field, and is commonly accepted as a test method for laboratory drag testing of skid resistance. Notable shortcomings of this equipment are that the BPT is complex and has an ineffective calibration process, it is expensive, a small difference in the pendulum spring displacement causes the PV to change significantly, and the tester cannot provide frictional resistance values above 30 mph.

Currently, MD SHA has two BPT's which are being used to determine the British Pendulum Number (BPN) of coarse HMA aggregate. In order to determine if the two pieces of equipment produce similar results when the same type of aggregates are tested and if they are operator independent (the test results are repeatable irrespective of material, equipment, or operator) a study was conducted to evaluate the repeatability of the test procedure and operator.

The subsequent sections of this chapter discuss (1) an overview of this study, (2) analysis of data variability between swings/runs, (3) data, analysis and observations of each test (material variability, equipment variability, and operator variability), and, (4) the conclusions and recommendations concerning this phase of the study, and (5) results of a process improvement strategy.

6.2. Overview of the Study

The purpose of this study was to determine if the BPT is a viable laboratory test method to determine the frictional characteristics of coarse aggregate specimens. In order to determine this, three independent studies were performed as follows:

- Material Variability: Performed to determine the statistical variability of three types of aggregates – control (Ottawa sand), carbonate, and non-carbonate. This study was performed to determine specimen variability for one operator using one piece of testing equipment.
- Equipment Variability: Performed to determine if test results from two independent BPT test devices are statistically similar.

- Operator Variability: Performed to determine if test results from two equipment operators are statistically similar.

The number and type of independent specimens used for each study is presented in Figure 6-1

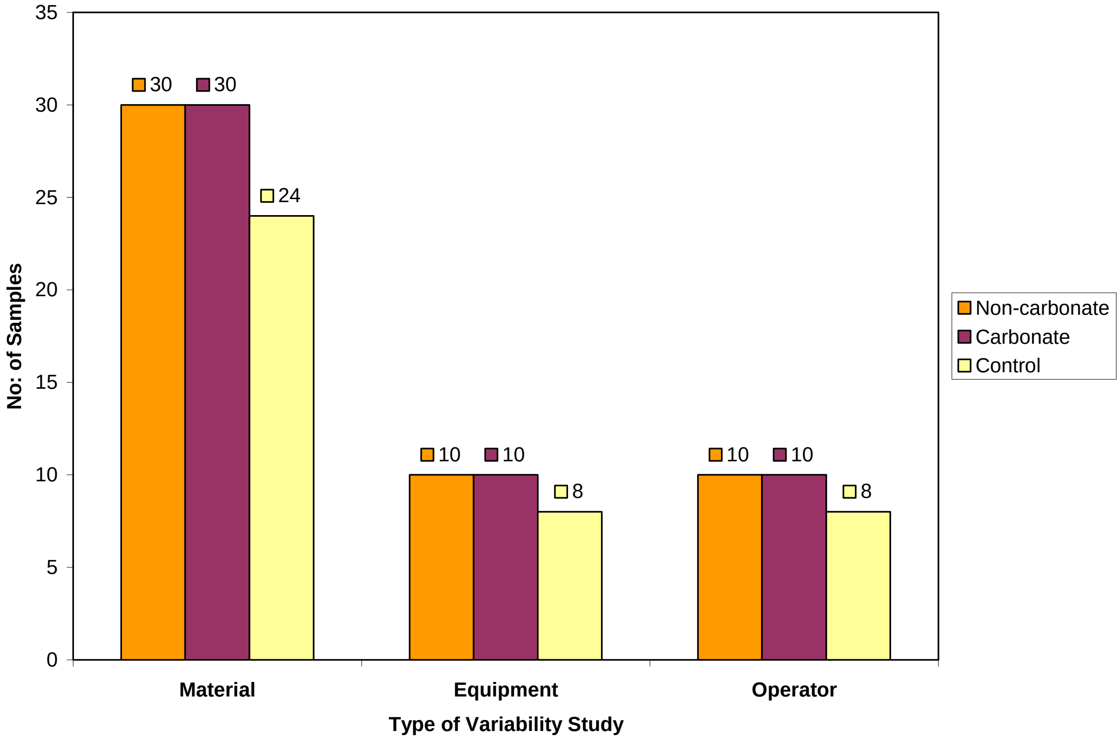

Figure 6-1. **Number of independent specimens used for each study**

6.3. A Note on Swing Analysis

For a particular test on a specimen, the ASTM Standard E 303-93(1998) states that the PV readings must be recorded from swings/runs 2 to 5. However, for this particular study, the PVs were recorded from swings/runs 2 to 10 since MD SHA was taking readings of more than 5 swings when performing the test prior to this study. Therefore, in order to determine if there was a significant difference if the readings are taken from swings/runs 2 to 5 (ASTM specification) compared to swings/runs 2 to 10, the readings were recorded and analyzed from swings/runs 2 to 10 and swings/runs 2 to 5. Additionally, the readings were also analyzed from swings/runs 7 to 10 for all test results of this study. Table 6−1 documents the average and standard deviation values for the two aggregate types used for material, equipment and operator variability studies. Table 6−2 shows the results of the F-tests performed to determine the variability between swings/runs 2 to 10, swings/runs 2 to 5 and swings/runs 7 to 10.

Table 6–1. Analysis of swings/runs

Variability Study*	Carbonate Aggregate						Non-carbonate Aggregate					
	Run 2 to 10		Run 2 to 5		Run 7 to 10		Run 2 to 10		Run 2 to 5		Run 7 to 10	
	Avg.	Std Dev.	Avg.	Std Dev.	Avg.	Std Dev.	Avg.	Std Dev.	Avg.	Std Dev.	Avg.	Std Dev.
M	**30.6**	**1.6**	**30.5**	**1.5**	**30.7**	**1.7**	**31.4**	**1.0**	**31.1**	**1.0**	**31.7**	**1.1**
E-1	**33.2**	**1.9**	**33.2**	**1.9**	**33.2**	**2.0**	**33.7**	**2.9**	**33.2**	**2.7**	**34.2**	**3.0**
E-2	**33.6**	**1.1**	**33.8**	**1.3**	**33.3**	**1.0**	**33.6**	**2.5**	**33.8**	**2.6**	**33.4**	**2.6**
O-1	**31.0**	**1.3**	**30.8**	**1.3**	**31.2**	**1.4**	**30.3**	**0.9**	**29.7**	**0.5**	**30.8**	**1.4**
O-2	**30.7**	**1.6**	**30.5**	**1.7**	**31.0**	**1.4**	**30.9**	**1.5**	**30.6**	**1.5**	**31.4**	**1.7**

* *M: Data obtained during material variability study*
E-1: Data obtained using BPT 1 (8965 Stanley)
E-2: Data obtained using BPT 2 (A9537 Wessex)
O-1: Data recorded by Operator 1
O-2: Data recorded by Operator 2

Table 6–2. F-test results for within swings/runs variability

Variability Study*	Carbonate Aggregate						Non-carbonate Aggregate					
	Between Run 2 to 10 and Run 2 to 5		Between Run 2 to 5 and Run 7 to 10		Between Run 2 to 10 and Run 7 to 10		Between Run 2 to 10 and Run 2 to 5		Between Run 2 to 5 and Run 7 to 10		Between Run 2 to 10 and Run 7 to 10	
	F	Fcr	F	Fcr	F	Fcr	F	Fcr	F	Fcr	F	Fcr
M	0.74	1.86	0.46	1.86	0.69	1.86	0.70	1.86	0.36	1.86	0.60	1.86
E-1	0.98	6.39	0.90	6.39	0.92	6.39	0.94	6.39	0.95	6.39	0.92	6.39
E-2	0.81	6.39	0.60	6.39	0.78	6.39	0.99	6.39	0.95	6.39	0.94	6.39
O-1	0.99	6.39	0.86	6.39	0.87	6.39	0.29	6.39	0.09	6.39	0.46	6.39
O-2	0.88	6.39	0.74	6.39	0.86	6.39	0.98	6.39	0.86	6.39	0.87	6.39

* *M: Data obtained during material variability study*
E-1: Data obtained using BPT 1 (8965 Stanley)
E-2: Data obtained using BPT 2 (A9537 Wessex)
O-1: Data recorded by Operator 1
O-2: Data recorded by Operator 2
Note: F – F value; Fcr – F critical value

As seen in Table 6−2, there is no significant difference between the averages from swings/runs 2 to 10, swings/runs 2 to 5 and swings/runs 7 to 10 since in all the cases F-value is **less than** F-critical value. Therefore, the data from swings/runs 2 to 5 (ASTM criteria) were used for analysis in this study.

6.4. Material Variability Study

To determine the within material variability for carbonate aggregate, 30 aggregate specimens and 12 control specimens were tested. For the non-carbonate material variability study, 30 aggregate specimens and 12 control specimens were tested.

Control Samples

Table 6−3 contains the test results for the control samples used for the carbonate material variability study and Table 6-4 shows the analysis results for the control samples used for the carbonate material variability study. Similarly, Table 6−5 contains the test results for the control samples used for the non-carbonate material variability study and Table 6−6 shows the analysis results for the control samples used for the non-carbonate material variability study.

Table 6–3. Control sample data - carbonate material variability study

Sample No.	Initial Polish Value*	Final Polish Value*
M029	33.8	29.5
M030	39.8	29.3
M031	33.5	27.3
M032	40.3	27.0
M033	36.5	28.5
M034	33.3	28.8
M035	30.0	28.3
M036	34.5	26.5
M037	35.3	27.5
M038	35.0	27.0
M039	33.5	26.8
M040	40.8	27.0

** Average of 4 swings/ runs*

Table 6–4. Control sample analysis - carbonate material variability study

	Initial Polish Value	**Final Polish Value**
No: of samples tested:	12	12
Average:	**35.5**	**27.8**
Minimum:	30.0	26.5
Maximum:	40.8	29.5
Standard Deviation:	3.3	1.0
95% Confidence:	1.8	0.6
Mean+confidence:	37.3	28.4
Mean-confidence:	33.7	27.2

Table 6–5. Control sample data - non-carbonate material variability study

Sample No.	**Initial Polish Value***	**Final Polish Value***
M017	29.8	29.5
M018	27.3	29.3
M019	28.8	28.5
M020	32.5	29.3
M021	32.3	28.5
M022	31.5	29.0
M023	30.3	27.5
M024	30.3	27.8
M025	35.5	25.3
M026	30.0	25.3
M027	34.3	25.0
M028	31.8	24.8

** Average of 4 swings/ runs*

Table 6–6. Control sample analysis - non-carbonate material variability study

	Initial Polish Value	**Final Polish Value**
No: of samples tested:	12	12
Average:	**31.2**	**27.5**
Minimum:	27.3	24.8
Maximum:	35.5	29.5
Standard Deviation:	2.3	1.9
95% Confidence:	1.3	1.1
mean+confidence:	32.5	28.5
mean-confidence:	29.9	26.4

Based on the analysis shown in Table 6−4 and Table 6−6, the control samples **do not meet** the ASTM criteria for either the average initial polish value (prior to polishing) of 38 ± 1 or the average final PV (after 10 hours of polishing) of 29 ± 1. Table 6−5 shows that one of the control samples has a final PV larger than the initial PV. These issues with the control samples are a significant finding.

As a result, it is recommended that the control sample preparation procedure be reviewed and amended as necessary to bring the control specimens into conformance with ASTM requirements.

Carbonate Material

Table 6−7 and Table 6−8 contain the resultant data and analysis, respectively, for the carbonate material variability study. Based on the analysis shown in Table 6−8, the carbonate material **does not meet** the ASTM criteria of a standard deviation of equal to or less than 1.2 for final PVs after 10 hours of polishing. However, the deviation from the ASTM specification is fairly small (1.2 versus 1.5).

Table 6–7. Carbonate aggregate specimen data

Sample No.	Initial Polish Value*	Final Polish Value*	Adjusted Final Polish Value**
M221	42.3	26.5	27.7
M222	44.0	28.5	29.8
M223	43.5	31.0	32.4
M224	42.5	29.8	31.1
M225	43.5	29.8	31.1
M226	45.5	32.0	33.4
M227	44.3	30.3	31.6
M228	43.5	31.5	32.9
M229	43.0	30.3	31.6
M230	43.0	30.0	31.3
M231	41.8	30.3	31.6
M232	42.3	32.5	33.9
M233	42.5	30.3	31.6
M234	40.8	29.0	30.3
M235	42.5	30.0	31.3
M236	39.0	27.8	29.0
M237	40.3	28.8	30.0
M238	43.3	27.5	28.7
M239	41.8	27.5	28.7
M240	44.3	29.5	30.8
M241	41.5	28.5	29.8
M242	41.5	30.0	31.3
M243	43.5	28.5	29.8
M244	43.8	28.5	29.8
M245	41.5	27.8	29.0
M246	43.5	28.5	29.8
M247	41.3	27.8	29.0
M248	42.0	29.0	30.3
M249	41.5	28.8	30.0
M250	40.0	27.5	28.7

** Average of 4 swings/ runs*

*** The value is adjusted based on established final polish value of the control specimen. The established final polish value of the control specimen is 29.*

Table 6–8. Carbonate aggregate specimen analysis

	Initial Polish Value	Final Polish Value	Adjusted Final Polish Value
No. of samples tested	**30**	**30**	**30**
Average	**42.4**	**29.2**	**30.5**
Minimum	**39.0**	**26.5**	**27.7**
Maximum	**45.5**	**32.5**	**33.9**
Standard Deviation	**1.4**	**1.4**	**1.5**
95% Confidence Interval	**0.5**	**0.5**	**0.5**
Mean + Confidence Interval	**43.0**	**29.8**	**31.1**
Mean – Confidence Interval	**41.9**	**28.7**	**30.0**

Non-Carbonate Material

Table 6-9 and 6-10 show the resultant data and analysis, respectively, for the non-carbonate material variability study.

Based on the analysis shown in Table 6-10, it can be seen that the non-carbonate material **meets** the ASTM criteria of standard deviation equal to or less than 1.2 for final PVs after 10 hours of polishing.

Conclusions

For some of the control samples, higher PVs were reported after polishing which is unreasonable. For the carbonate and non-carbonate aggregate testing more reasonable results were observed. Based on these findings, it was recommended that the sample preparation process for the control specimens be reviewed and possibly modified to bring the control specimen data into conformance with ASTM criteria.

Table 6–9. Non-carbonate aggregate specimen data

Sample No.	**Initial Polish Value***	**Final Polish Value***	**Adjusted Final Polish Value****
M121	45.0	29.8	31.4
M122	43.8	30.0	31.7
M123	44.0	30.3	32.0
M124	43.8	30.0	31.7
M125	42.0	30.0	31.7
M126	41.0	29.0	30.6
M127	40.5	29.8	31.4
M128	43.0	30.3	32.0
M129	42.5	30.0	31.7
M130	41.8	29.5	31.2
M131	42.5	29.0	30.6
M132	42.0	28.5	30.1
M133	41.8	29.8	31.4
M134	43.5	29.0	30.6
M135	39.5	28.8	30.4
M136	37.3	28.5	30.1
M137	40.0	32.5	34.3
M138	38.5	30.4	32.0
M139	39.5	28.5	30.1
M140	40.5	29.0	30.6
M141	43.3	29.3	30.9
M142	45.0	29.8	31.4
M143	42.5	29.0	30.6
M144	44.8	28.8	30.4
M145	42.8	29.8	31.4
M146	42.5	29.8	31.4
M147	42.5	27.3	28.8
M148	43.3	30.0	31.7
M149	40.0	30.0	31.7
M150	44.0	28.5	30.1

** Average of 4 swings/ runs*

** The value is adjusted based on established final polish value of the control specimen. The established final polish value of the control specimen is 29

Table 6–10. Non-carbonate aggregate specimen analysis

	Initial Polish Value	Final Polish Value	Adjusted Final Polish Value
No. of samples tested	30	30	30
Average	42.1	29.5	31.1
Minimum	37.3	27.3	28.8
Maximum	45.0	32.5	34.3
Standard Deviation	1.9	0.9	1.0
95% Confidence Interval	0.7	0.3	0.3
Mean + Confidence Interval	42.8	29.8	31.5
Mean – Confidence Interval	41.4	29.1	30.8

6.5. Equipment Variability Study

To study equipment variability, two pieces of equipment, one polisher, one operator, 8 control specimens, 10 carbonate aggregate samples and 10 non-carbonate aggregate samples were used.

Data and Analysis

Table 6−11 contains the data and Table 6−112 contains the analysis of the testing.

Conclusions

From Table 6−11, it can be seen that the control samples do not meet the ASTM criteria of either the average initial polish value (prior to polishing) of 38 ± 1 or the average final PV (after 10 hours of polishing) of 29 ± 1. Also, for some of the control samples, the final PV is higher than the initial PV.

In terms of variability between the carbonate and the non-carbonate aggregates, the repeatability and reproducibility standard deviation is slightly lower for carbonate aggregates compared to non-carbonate aggregates. However, the Student's t-test as seen in Table 6−12 shows that the variability is not statistically significant between the two aggregate types.

In terms of variability between the pieces of equipment, the repeatability and reproducibility standard deviation is not significantly different from each other. Also, the Student's t-test and F-test, as seen in Table 6−12, show that the variability is not statistically significant between the two pieces of equipment.

Therefore, it is concluded that both pieces of equipment are equally repeatable for performing this test.

Table 6–11. Equipment variability study results

Equipment	Material	Sample No.	Initial Polish Value*	Final Polish Value*	Adjusted Final Polish Value**
Equipment 1 (8965 Stanley)	Control	M001	35.3	30.3	N/A
		M002	27.8	29.5	
		M005	31.0	27.5	
		M006	29.5	27.8	
	Aggregate Type 1 (Non-carbonate)	M101	40.5	34.5	34.8
		M102	41.0	35.5	35.8
		M103	42.3	34.8	35.1
		M104	37.8	30.0	30.3
		M105	36.0	30.0	30.3
	Aggregate Type 2 (Carbonate)	M201	40.3	33.8	34.0
		M202	43.0	35.8	36.1
		M203	40.0	32.3	32.5
		M204	42.3	30.8	31.0
		M205	40.3	32.3	32.5
Equipment 2 (A9537)	Control	M003	26.8	27.0	N/A
		M004	35.5	27.5	
		M007	33.0	25.3	
		M008	34.5	27.3	
	Aggregate Type 1 (Non-carbonate)	M106	35.5	29.3	31.7
		M107	39.5	34.5	37.4
		M108	33.5	29.3	31.7
		M109	36.5	30.0	32.5
		M110	37.0	32.8	35.5
	Aggregate Type 2 (Carbonate)	M206	38.3	29.5	32.0
		M207	38.5	31.0	33.6
		M208	40.0	32.8	35.5
		M209	38.3	31.8	34.4
		M210	36.8	30.8	33.3

** Average of 4 swings/ runs*
*** The value is adjusted based on established final polish value of the control specimen. The established final polish value of the control specimen is 29*

Table 6–12. Student's T-test and F-test results for equipment variability study

Between Equipment/Material	Test Type (F or t-test)	Value of Statistic	Statistically Significant (Yes/No)
Between Material	T-value	0.00	No
	Critical T-value	2.10	
Between Equipment	T-value	0.17	No
	Critical T-value	2.10	
Between Equipment (Non-carbonate aggregate)	F-value	0.90	No
	Critical F-value	6.39	
Between Equipment (Carbonate aggregate)	F-value	0.48	No
	Critical F-value	6.39	

6.6. Operator Variability Study

To study operator variability, two operators, one piece of equipment, one polisher, 8 control specimens, 10 carbonate aggregate samples and 10 non-carbonate aggregate samples were used.

Data and Analysis

Table 6−13 contains the data and Table 6−14 contains the Student's t-test and F-test results for the operator variability study.

Conclusions

From Table 6−13 the control samples did not meet the ASTM criteria of either the average initial PV (prior to polishing) of 38 ± 1 or the average final PV (after 10 hours of polishing) of 29 ± 1. Also, for some of the control samples, the final PV is higher than the initial, as shown in Table 6−13.

Table 6−14 shows that the Student's t-test suggests that the variability is not statistically significant between the two aggregate types.

In terms of variability between the operators, the repeatability and reproducibility standard deviation is not significantly different between the operators. Also, the Student's t-test and F-test show that the variability is not statistically significant between the two operators. Therefore, it appears that the test is operator independent.

Table 6–13. Data of operator variability study

Operator	Material	Sample No.	Initial Polish Value*	Final Polish Value*	Adjusted Final Polish Value**
1	Control	M009	29.0	29.5	N/A
		M010	35.5	29.8	
		M011	35.8	28.5	
		M012	33.8	27.8	
	Aggregate Type 1 (Non-carbonate)	M111	40.0	28.8	28.9
		M112	40.5	29.3	29.4
		M113	40.5	30.0	30.1
		M114	40.0	30.0	30.1
		M115	40.3	29.8	29.9
	Aggregate Type 2 (Carbonate)	M211	41.8	30.0	30.1
		M212	44.0	30.5	30.6
		M213	43.3	31.5	31.6
		M214	41.0	32.3	32.4
		M215	39.5	29.0	29.1
2	Control	M013	22.5	29.3	N/A
		M014	26.0	25.8	
		M015	21.3	27.3	
		M016	22.0	25.3	

Operator	Material	Sample No.	Initial Polish Value*	Final Polish Value*	Adjusted Final Polish Value**
	Aggregate Type 1 (Non-carbonate)	M11	43.0	29.0	31.3
		M117	43.3	26.8	28.9
		M118	42.5	28.0	30.2
		M119	43.3	30.5	32.9
		M120	39.5	27.8	29.9
	Aggregate Type 2 (Carbonate)	M216	42.5	27.5	29.7
		M217	42.5	26.5	28.6
		M218	40.5	27.8	29.9
		M219	41.5	29.4	31.6
		M220	42.8	30.5	32.9

** Average of 4 swings/ runs*
*** The value is adjusted based on established final polish value of the control specimen. The established final polish value of the control specimen is 29.*

Table 6–14. Student T-test and F-test results for operator variability study

Between Operator/Material	Test Type (F or t-test)	Value of Statistic	Statistically Significant (Yes/No)
Between Material	T-value	0.44	No
	Critical T-value	2.10	
Between Operator	T-value	0.32	No
	Critical T-value	2.10	
Between Operator (Non-carbonate aggregate)	F-value	0.07	No
	Critical F-value	6.39	
Between Operator (Carbonate aggregate only)	F-value	0.59	No
	Critical F-value	6.39	

6.7. Improvement Process

The primary improvement made by MD SHA to ameliorate the control sample results was to redevelop the procedure used to prepare the control specimens. After a trial-and-error approach, the procedure documented in Appendix A was developed. The primary difference between the ASTM and the MD SHA procedure is using reduced amounts of resin for preparing MD SHA BPT samples.

Subsequently, the preparation and testing of control samples using the new procedure was performed from July 2008 to November 2008. All specimens were tested using the same polisher and British pendulum.

During testing, the average of runs 2 to 5 was recorded. The initial PV-i (0 hrs of polishing) was recorded. Later the PV was recorded after 1, 2, 4, 6, 8, and 10 hours of polishing. The testing involved polishing and testing 4 control samples along with 10 aggregate samples in each series of testing. Table 6−15 shows the results of the average of the 4 control samples in each series and Table 6−16 show the analysis of the results. Detailed control sample testing results are shown in Table 6−17.

Table 6–15. Summary results of control samples testing

Series	***Polish Value - hrs of polishing***						
	PV-0	***PV-1***	***PV-2***	***PV-4***	***PV-6***	***PV-8***	***PV-10***
08-2	49	37	35	33	32	31	30
08-3	48	37	35	33	32	30	29
08-4	48	35	34	32	32	30	29
08-5	46	36	34	33	31	31	30
08-6	50	37	36	34	31	30	29
08-7	49	36	33	33	31	31	31
08-8	48	36	35	33	32	31	30

Table 6–16. Analysis of the results

	Initial Polish value *(PV-i)*	**Final Polish Value *(PV-10)***
No: of samples tested:	28	28
Average:	48.2	29.5
Minimum:	41.0	28.0
Maximum:	54.0	31.0
Standard Deviation:	3.4	1.0

Table 6–17. Detailed results of control sample testing

	Polish Value - hrs of polishing						
Series	***PV-0***	***PV-1***	***PV-2***	***PV-4***	***PV-6***	***PV-8***	***PV-10***
08-2	52	37	36	34	33	32	31
	54	40	36	33	33	31	30
	48	35	34	33	31	31	29
	42	34	34	33	31	30	29
08-3	49	36	35	32	31	30	28
	46	36	34	32	31	29	28
	45	36	34	32	31	30	29
	51	38	37	34	33	31	31
08-4	46	35	34	32	32	31	30
	53	37	37	33	33	31	30
	52	34	34	30	29	29	28
	41	35	32	32	32	30	29
08-5	47	37	35	31	30	30	29
	47	35	34	33	30	30	29
	44	35	34	33	32	31	31
	47	36	34	33	31	31	29
08-6	51	38	36	34	32	31	29
	47	37	36	34	31	30	30
	46	36	35	34	30	30	28
	54	37	36	32	31	30	28
08-7	51	38	33	31	31	30	30
	50	36	32	32	31	31	31

	Polish Value - hrs of polishing						
Series	***PV-0***	***PV-1***	***PV-2***	***PV-4***	***PV-6***	***PV-8***	***PV-10***
	51	37	34	34	32	32	31
	45	34	33	33	30	30	30
08-8	49	36	34	34	32	31	29
	50	36	35	33	32	29	29
	46	36	35	33	32	31	30
	46	36	35	33	31	31	30

As seen in Table 6−15 and Table 6−16, the initial PVs of the samples prior to polishing do not meet the ASTM requirement of 38 ± 1. However, the PVs of the samples after 10 hours of polish do meet the ASTM criteria of 29 ± 1.

Figure 6-2 shows the decrease of PVs over the testing period. It can be seen from the figure that during the first hour of polishing the PVs decrease significantly. However, after an additional hour of polishing the PVs did not decrease as significantly as after the first hour of polishing. Additionally, it can be seen that the rate of decrease of the PVs of all the samples is relatively consistent.

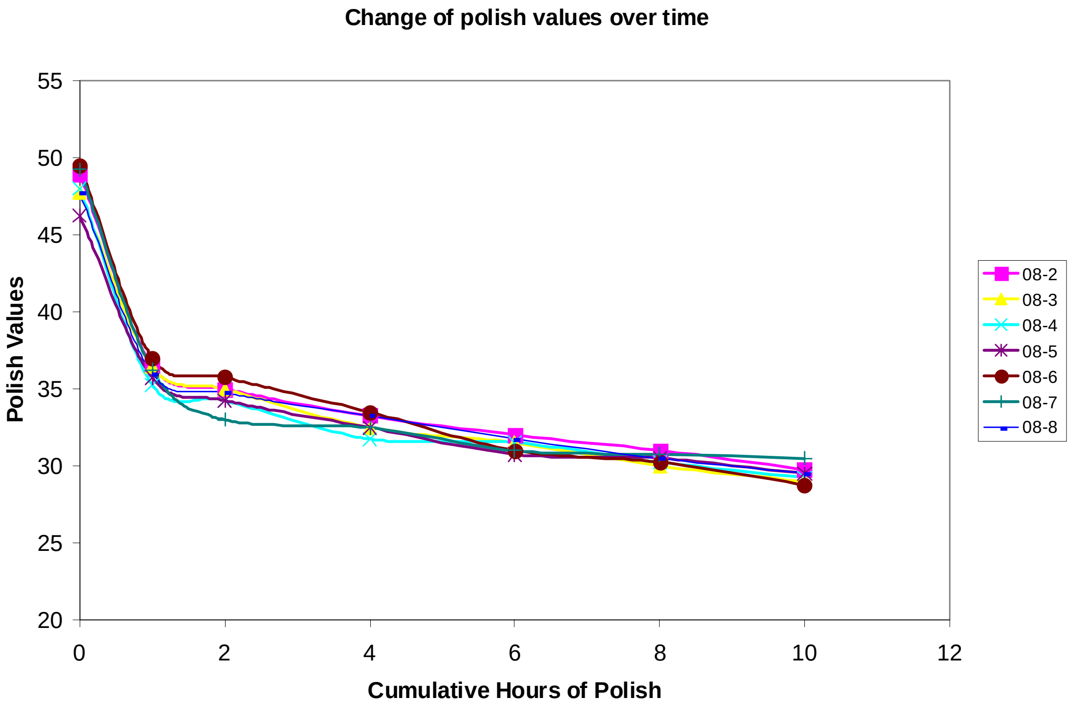

Figure 6-2. Control specimen data using new procedure

Conclusions

The test improvement strategy yields more consistent control specimens. Also, the control specimens now meet the ASTM requirement for final PV. The conclusions and recommendations are presented based upon a review of the data.

- The new procedure significantly reduces control specimen variability.
- After modifications to the ASTM procedure of preparation of control samples, the samples tested did not meet the ASTM criteria for initial PVs but meet the ASTM criteria for final PVs after 10 hours of polishing.
- The purpose of the control specimens is to provide a means to judge the variability of the test machinery and point out when the system is not working as intended. Therefore, while the initial PVs do not meet ASTM requirements, the specimens appear consistent and can be used as control specimens for the above-stated purpose. With this in mind, it is essential that MD SHA establish (if it does not already have) a control specimen chart (spreadsheet) to document the performance of the control specimens for each test performed and create a mechanism for flagging data that does not meet test requirements. This flag should be based upon the 29 ± 1 ASTM criteria for final polish value. A more robust procedure may be to check the initial polish value to see if it is in the range of 40 to 50. An even more robust check would be to check the entire polish curve at each time period to determine if the values are within an expected range.
- It appears that the current testing process meets the intent of the ASTM procedure and can be continued into the future.
- The British Wheel and Pendulum should be calibrated according to manufacturer specifications.

The revised standard taking into account these recommendations is included in Appendix A.

CHAPTER 7. PHASE 2 - INVESTIGATION OF NCAT POLISHER AND DFT

7.1. Introduction

At the conclusion of phase 1 of this study, MD SHA made the determination to move forward with examining the aggregate polisher developed by the National Center for Asphalt Technology (NCAT) and the Dynamic Friction Tester (DFT) to replace the MD Track test equipment. A visit was made to Purdue University to evaluate the Polisher and DFT hands-on. After an eighteen month procurement and fabrication period, the aggregate polisher was obtained from the North Central Superpave Center (NCSC) located at Purdue University. Purdue has pioneered work with using the NCAT polisher and DFT to measure the frictional characteristics of asphalt specimens. At the same time, MD SHA obtained a DFT for testing samples at various intervals of polishing. The purpose of this task was to use this equipment to develop a test procedure for use by MD SHA.

7.2. Variability Analysis

At this stage in the study, it had been proposed that the NCAT polisher be used for polishing aggregate samples and the aggregate's frictional resistance be measured with the DFT. While there is an ASTM standard for performing DFT testing, there is no documentation on the DFT test being used specifically for aggregates. One of the objectives of this study was to determine the possibility of testing the aggregate samples using the DFT. The study involved determining the variability between aggregate samples.

The objective of this task is to analyze the results of the aggregate friction variability study to determine the following:

- Number of revolutions required to reach terminal polish
- DFT measurement speeds to be reported
- Number of DFT tests required per stop
- Number of stops required
- Number of samples required to characterize aggregate friction
- Reasonableness of the test procedure

Procedure

The study consisted of two types of aggregates:

1. HDG samples with a known history of relatively high PVs and
2. LFG with a known history of relatively low PVs.

Five samples from each source were tested to at least 100,000 revolutions. DFT measurements were taken at 10,000 revolution increments (referred to as a "stop" to be consistent with MD

SHA terminology). A total of ten DFT measurements were taken at each stop. One operator performed all of the testing.

Number of Revolutions Required

The originally proposed study limited the number of revolutions of the Polisher on the aggregate specimen to 100,000 (with three wheels, this means that a Polisher tire travels over a given spot on the aggregate surface 300,000 times). For some specimens, polishing was allowed to continue to 150,000 revolutions (450,000 passes). Average data from each stop were reviewed to identify when the DFT values stabilized and thus "terminal polish" achieved.

For this study, the terminal polish value was identified as occurring when less than a 1 percent change in the results occurred from the prior reading at the same speed. An example of a typical plot of number of revolutions of the Polisher versus DFT test result is shown in Figure 7-1.

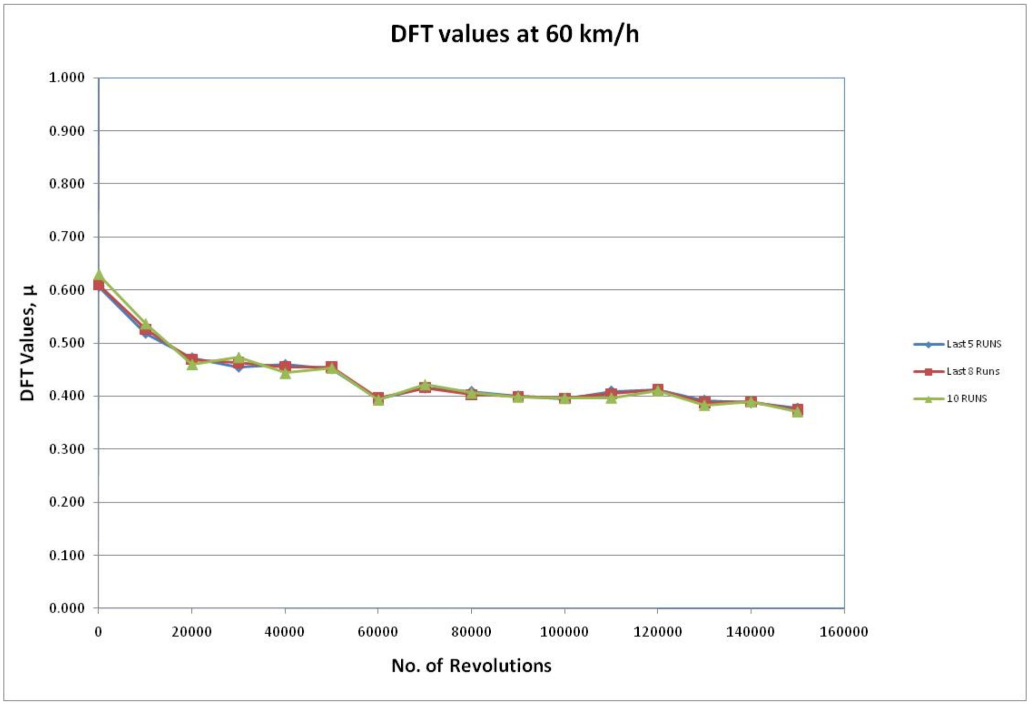

Figure 7-1. Typical plot of DFT versus number of revolutions

Using the data from all stops, the terminal value for each speed is presented in Table 7−1. For reasons discussed later, data from 70 and 80 km/h should not be used for analysis of DFT data on aggregates.

Table 7–1. Terminal number of revolutions

Aggregate	Speed, km/hr	Terminal Revolutions	Terminal DFT, µ
HDG	10	90,000	0.447
	20	50,000	0.472
	30	50,000	0.454
	40	90,000	0.409
	50	90,000	0.397
	60	40,000	0.433
	70	50,000	0.458
	80	90,000	0.423
LFG	10	70,000	0.334
	20	60,000	0.339
	30	50,000	0.339
	40	60,000	0.338
	50	50,000	0.333
	60	60,000	0.339
	70	40,000	0.384
	80	70,000	0.396

From this analysis, it can be seen that the terminal DFT value (expressed as coefficient of friction, µ, a dimensionless value) varies from 40,000 to 90,000 revolutions for these two aggregates. In general, the softer aggregate reached terminal polish (50,000 to 70,000 revs) faster than the higher polish aggregate (40,000 to 90,000 revs), as could be reasonably expected.

Based on these data, it was recommended that polishing continue to be performed to 100,000 revolutions. This allows higher polish aggregates time to reach terminal polish.

For the purposes of the variability study, ten DFT tests were performed at 10,000 revolution increments. This was been done to view the shape of the µ/DFT curve. For production testing purposes, the shape of the curve has no analytical value – we are only interested in the initial and terminal polish values. Therefore, it was recommended that DFT tests be performed only for an initial reading (0 revs) and a terminal reading (100,000 revs). Intermediate readings may be desired to make sure the test is progressing without unreasonable fluctuations in the test results, but this is optional. Performing the DFT test only at the initial and terminal number of revolutions will increase the efficiency of the test and reduce wear and tear on the DFT. It also reduces the cost of replacing the DFT rubber sliders.

DFT Measurement Speeds Needed

The next analysis was performed to evaluate the requirement for reporting data at multiple DFT speeds. For the variability study, data was summarized at 10 km/h intervals (10, 20, 30, 40, 50, 60, 70, and 80). The ASTM standard that governs this test (ASTM E1911, Standard Test Method for Measuring Paved Surface Frictional Properties Using the Dynamic Friction Tester) requires reporting the DFT measurement at 20, 40, 60, and 80 km/h. Values at 20 km/h generally are thought to correspond with British Pendulum test results while data at 60 km/h are generally believed to correspond with locked wheel skid test results (Reference 6). Upon review of the data as testing progressed, it became obvious that the DFT values at 0, 70 and 80 km/h were not reasonable. A typical plot of μ versus DFT speed is shown in Figure 7-2.

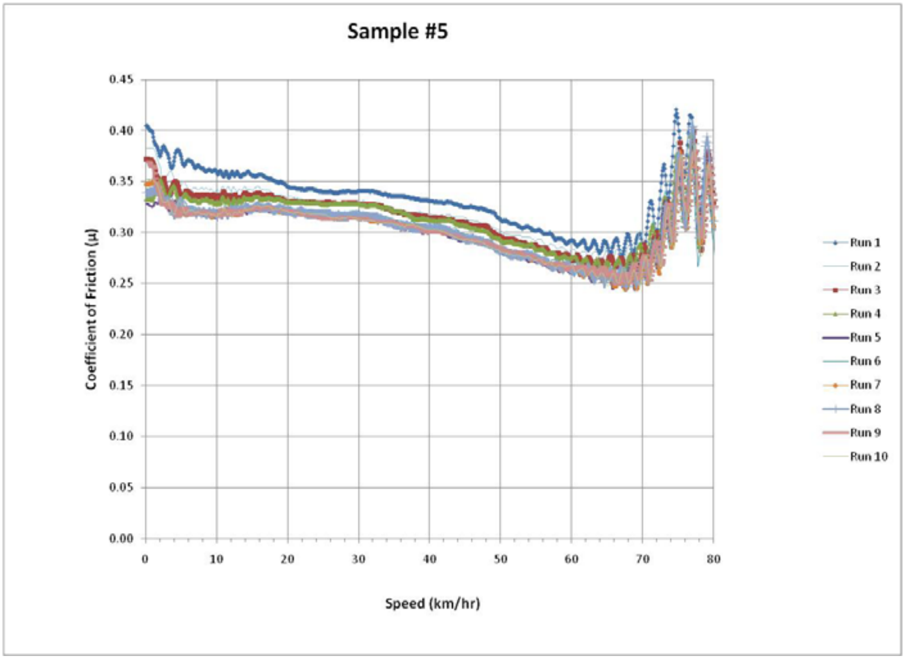

Figure 7-2. Typical DFT test speed versus μ

In general, the variability between tests of the data at 70 and 80 km/hr speeds was higher for each sample than data collected at other speeds. For the LFG samples, the average terminal DFT values at 70 and 80 km/hr are larger than the upper limit of the 95 percent confidence interval for the average terminal DFT for the other speeds as shown in Table 7−2. These reviews indicated the data at 70 and 80 km/hr were not consistent with other observations.

Table 7–2. Comparison of average - LFG specimens

Statistic	Speed, km/hr				
	20	**40**	**60**	**70**	**80**
Average	0.339	0.335	0.327	0.385	0.387
Upper Limit	0.378	0.373	0.366	0.424	0.425
Lower Limit	0.300	0.296	0.288	0.346	0.348

Based upon the ASTM standard and these test results, it was recommended that data at 20, 40, and 60 km/h be reported for each test result. The value at 60 km/h should be used to assess whether an aggregate is high or low polish for aggregate bulletin and materials acceptance purposes. According to the ASTM procedure and other literature, this value most closely correlates to the locked-wheel skid tester, and thus correlates with expected in-place field conditions. In order to account for changes in correlations that may be created once a full round of data has been collected and other MD SHA research studies are completed, the full data trace for each DFT test should be stored for possible future evaluation in the case that new correlations are developed in the future.

Number of DFT Tests Required Per Stop

In order to evaluate test variability, 10 DFT tests were performed at each stop for this study. ASTM E1911 requires only 1 test at each stop. The ASTM E1911 standard's precision statement states, "the standard deviation of eight measurements on the same test surface ranged from 0.044 at 30 km/h to 0.038 at 60 km/h." In order to test this statement, an analysis was performed at each stop to determine the standard deviation using eight measurements. Out of 200 measurements at 30 and 60 km/h, only two (1%) test results fall outside the ASTM precision statement. The other 198 measurements fall within the precision statement.

In addition to the above analysis, the variability of repeat data for each stop was evaluated for each of the 10 tests at a given speed. A confidence interval was established for each set of 10 tests and the first test result was reviewed in comparison to the confidence interval. The confidence interval was determined using the following equation:

$$\text{Avg} \pm z \times 0.044/\sqrt{n}$$

Where:

Avg = the average 10 tests for each combination of speed and revolution
z = the z-statistic used to calculate the confidence interval at a 95 percent level of confidence = 1.96
0.044 = the estimated precision level as provided by ASTM E1911
n = 10, the number of runs performed at each stop

In most cases (more than 95%), the first test did not fall within the 95 percent confidence interval. Only slightly fewer values, but still more than 95%, did not fall within an 80 percent confidence interval of the mean for each set of 10 tests.

In reviewing the data, it was apparent that DFT test results change as the number of tests increase. It was not possible to state whether this difference occurs due to wear of the aggregate, water saturation of the aggregates, wear of the equipment, or some other factor. The DFT value is generally, though not always, higher for the first few tests than for the remaining tests.

Further review identifies that for 99 percent of the data sets, the average of runs 2, 3, and 4 provides a result that falls within the 95 percent confidence interval of all 10 runs. Therefore, it is recommended that for each stop, a set of 4 runs be completed and the data averaged for runs 2, 3, and 4. The average of runs 2, 3, and 4 should be reported as the aggregate friction value.

Number of Specimens Required

As mentioned previously, ASTM E1911 identifies a precision for the test procedure ranging from a standard deviation of 0.044 to 0.038 depending upon the speed of the test. This standard deviation is used to evaluate the number of specimens required for testing.

The terminal DFT value is evaluated using the data collected at speeds of 20, 40, and 60 km/h and at five stops. The average DFT value across the five samples were determined and using the standard deviation of 0.044 from the ASTM standard a 95 percent confidence interval was developed using the following equation:

$$\text{Avg} \pm z \times 0.044/\sqrt{n}$$

Where:

Avg = the average of the terminal values for each of runs 2, 3, and 4 of the five samples tested of each aggregate source.
z = the z-statistic used to calculate the confidence interval at a 95 percent level of confidence = 1.96
0.044 = the estimated precision level as provided by ASTM E1911
n = the number of runs used in calculating the average

The individual sample data were reviewed based on the confidence interval determined for each speed. Table 7−3 presents the results of that review. The values presented in bold fall outside the confidence interval.

Table 7–3. Comparison of sample data to 95 percent confidence interval

Aggregate	**Sample**	**Speed, km/h**		
		20	**40**	**60**
HDG	1	0.435	0.399	0.397
	2	0.479	0.456	0.440
	3	0.470	0.463	**0.418**
	4	**0.390**	**0.369**	0.365
	5	0.462	0.425	0.415
	Average	0.447	0.422	0.407
	Upper Limit	0.497	0.472	0.457
	Lower Limit	0.397	0.373	0.357
LFG	1	0.324	0.317	**0.290**
	2	0.349	0.363	0.386
	3	**0.409**	0.373	0.363
	4	**0.288**	0.306	0.333
	5	0.344	0.350	0.340
	Average	0.342	0.342	0.342
	Upper Limit	0.392	0.392	0.392
	Lower Limit	0.292	0.292	0.292

This review shows that in order to identify that the value reviewed is within a 95 percent level of confidence of the mean, a minimum of three samples is required, and the results averaged. The 95 percent confidence interval is a fairly high standard but it was felt that due to the importance of the aggregate friction values to both SHA and its partner aggregate producers, that this level of confidence in the test results is desired. While this recommendation has implications to the cost and turnaround time of the test procedure, other recommended test efficiencies recommended should ameliorate this impact significantly.

Reasonableness of the Test Procedure

The next step in reviewing the test procedure was to compare the results between the HDG sample and the LFG sample. Figure 7-3 provides the average polish values for the HDG and LFG samples at speeds of 20, 40, and 60 km/h. This comparison is provided in Figure 7-4 with each speed of testing represented by a different series. The largest difference in DFT values is observed at the lower speeds and generally at lower revolutions. The HDG sample exhibited higher DFT values than the LFG sample indicating that the HDG aggregate has a higher coefficient of friction of the two sources.

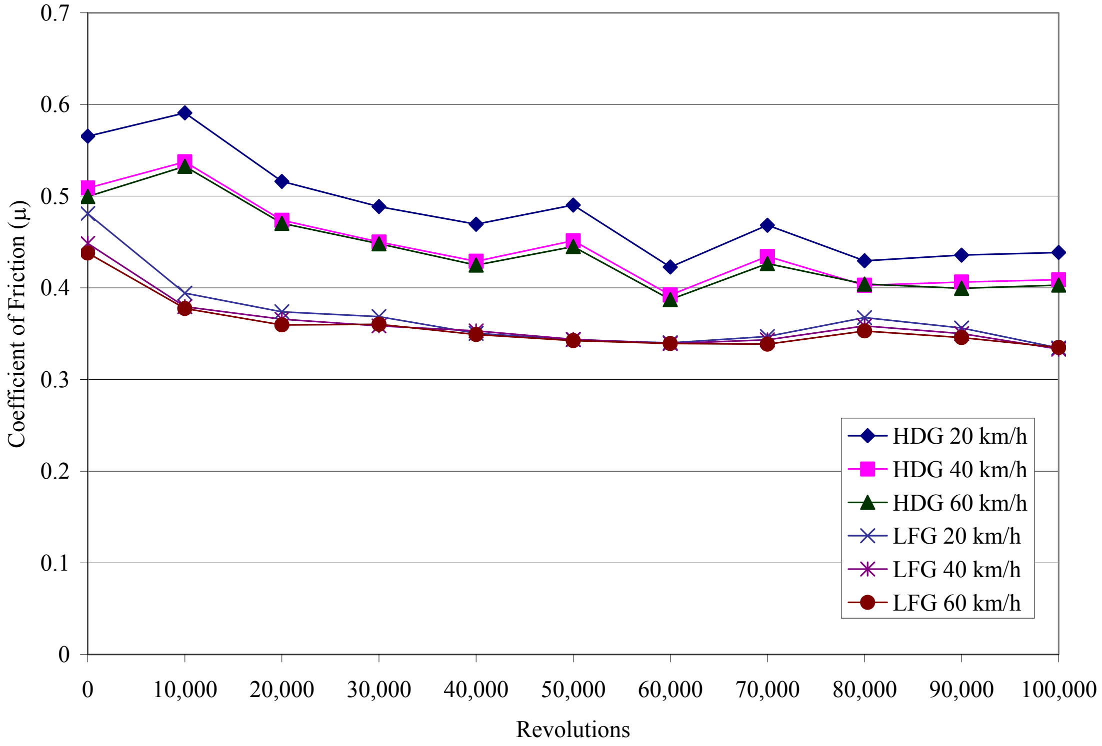

Figure 7-3. Average Polish Value for HDG and LFG aggregates

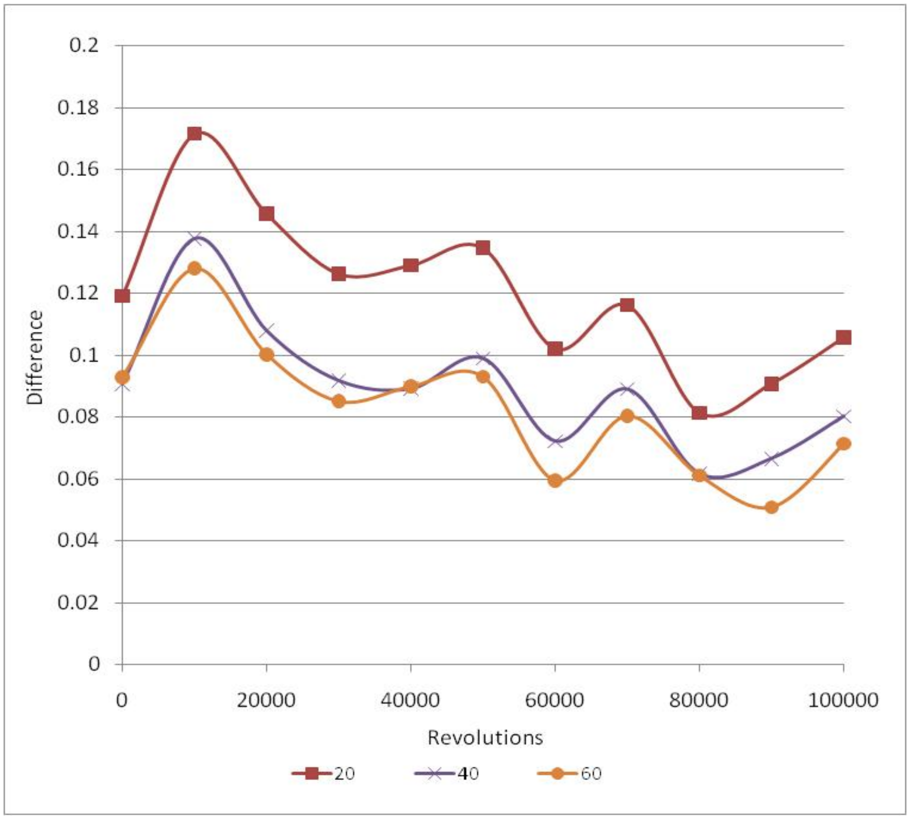

Figure 7-4. Difference between HDG and LFG DFT values

Based on a review of all of the data results for this variability study, it appears that the test procedure is repeatable, is showing a difference in friction values between low and high polish samples, and is a viable test procedure to determine the polish value of aggregate source materials.

7.3. Test Procedures

A specification for polishing and testing aggregate samples was developed based on the results of the portion of the study discussed in this chapter. The specification requires a minimum of 5 lbs of aggregate passing the ½-inch sieve and retained on the ⅜-inch sieve. The aggregate are spread in a single layer into the mold and epoxy is used to hold them in place. An example of a typical sample is illustrated in Figure 7-5.

Prior to any polishing the aggregate was tested using the DFT to provide an initial friction value. Four runs are performed on the specimen with results recorded at individual speeds of 20, 40, and 60 km/h.

Figure 7-5. Example specimen ready for testing

After initial testing, the sample is subjected to polishing using the NCAT polisher. Polishing is performed for 100,000 revolutions as shown in Figure 7-6. Once the polisher has completed 100,000 revolutions on the specimen, the specimen is tested again with the DFT. As with the initial testing, a minimum of four runs are completed on the specimen with friction values recorded at 20, 40, and 60 km/h.

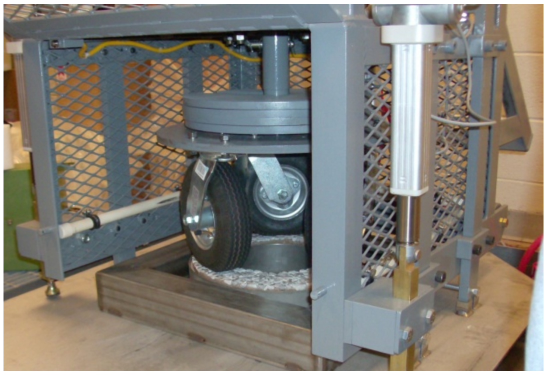

Figure 7-6. NCAT polisher with specimen in place

The final friction value recorded at 60 km/h is used to identify the frictional characteristics of the aggregate source.

CHAPTER 8. CONCLUSIONS AND RECOMMENDATIONS

The study presented here wasperformed to assist MD SHA in improving their ability to identify the field performance of aggregates in HMA with respect to friction. As part of this study, the following conclusions and recommendations were developed:

- There is no laboratory test used by a state DOT that can predict aggregate friction field performance with a high degree of certainty.
- The British Pendulum Tester is a fairly robust test with low variability associated with the device and operator.
- The control specimens for the British Pendulum Tester are used as a means to judge the variability of the test machinery and identify when the system is not working as required. Therefore, while the initial PVs do not meet ASTM requirements, the specimens appear consistent and can be used as control specimens for this purpose. It is essential that MD SHA establish a control specimen chart to document the performance of the control specimens for each test performed and create a mechanism for flagging data that does not meet test requirements. The most robust check on these values would be a review of these data would be to check the entire polish curve at each time period to determine if the values are within an expected range.
- The BPT is small, portable, easy to use, and is commonly accepted as a laboratory test of skid resistance.
- The combination of the NCAT polisher and DFT provide another robust means for evaluating aggregate friction characteristics.
- The DFT is also compact, portable, and easy to handle.
- The DFT measures friction as a function of speed and is the only instrument directly measuring the coefficient of friction.
- The DFT can be used in the field as well as in the laboratory making it possible to pursue further study to equate results of testing with the DFT in the laboratory with field performance of aggregates.

As a result of this study, the project team concluded that the NCAT Polisher and DFT combination could be a viable test procedure for Maryland to determine aggregate friction values. Two draft testing specifications have been developed. The specifications are included in Appendix B and C.

In order to implement these test procedures, testing should be conducted by MD SHA to determine the range of friction values for MD SHA sources. This data, along with historical data stored by MD SHA and BPT test results, should be used to determine breakpoints for the coefficient of friction value that can be used to determine high polish values.

In addition, it is recommended that a study be performed to correlate lab derived aggregate friction values with field performance of as-placed HMA mixtures. With this correlation, lab results can be more closely tied with field performance to enable better selection and control of aggregates for high polish values HMA mixtures.

Appendix A

Revised MSMT
Laboratory Method of Measuring Frictional Properties of Aggregates Using the British Pendulum Tester

Recommended Approval	______________________ Team Leader Date ______________________ Regional Engineer Date	Maryland Department of Transportation State Highway Administration Office of Materials Technology MARYLAND STANDARD METHOD OF TESTS	
Approved:	______________________ Deputy Chief Engineer Date	**LABORATORY METHOD OF MEASURING FRICTIONAL PROPERTIES OF AGGREGATES USING BRITISH PENDULUM TESTER**	**MSMT X**

SCOPE:

The procedure is used to determine the residual polish value, (RPV-n) of aggregates from each source.

REFERENCE DOCUMENTS:

D 3319-06	– Standard Practice for the Accelerated Polishing of Aggregates Using the British Wheel
E 303-93	– Standard Test Method for Measuring Frictional Properties Using the British Pendulum Tester

TERMINOLOGY:

Polish Value (PV-*n*) – As stated in D 3319-06 "a measure of the state of polish by a test specimen subjected to the specific hours (n) of accelerated polishing using the materials, equipment, and procedures described in this method. The measurement is made using the British Pendulum Tester and Test Method E 303".

Initial Polish Value (PV-*i*) – It is the initial British Pendulum Number (BPN) of the test specimens before they are polished using the British Wheel.

Final Polish Value (PV-*10*) – It is the British Pendulum Number (BPN) of the test specimens after they are polished for *10* hours using the British Wheel.

SIGNIFICANCE AND USE:

The values obtained from this procedure are used to determine the ability of the coarse aggregates to resist polishing under traffic and to classify the aggregates accordingly.

SAMPLE PREPARATION

Aggregates Sample Preparation – use the procedure described in D 3319-06.

Control Sample Preparation – use the procedure described below.

The preparation of the control samples is carried out in two parts. The various components used in each part and the process of preparing the samples are discussed below.

Part 1 Components

148 gms	Resin (Isophthalic Tooling/Structure)
44 gms	Wollastonite (NYAD 400 Extender Pigment)
5.5 gms	Silica (Amorphous Fumed Silica, 150 grit size)
2.0 ml	Hardener (Methyl Ethyl Keyton Peroxide)
1184 gms	Grade 20-30 Ottawa Sand

Part 2 Components

888 gms	Resin
264 gms	Wollastonite
33 gms	Silica
12 ml	Hardener (peroxide)

Initially, the components in part 1 are mixed under a well ventilated fume hood. In a large container (1/2 gal. plastic jug cut down) weigh out 148 gms resin. Set aside in hood. This container will be used as a mixing bowl and gets thrown away after the molds are filled. In a second container weigh out 44 gms wollastonite and 5.5 gms silica. The container needs to be large enough to hold the wollastonite and silica. It can be reused since it holds two dry materials that do not react with each other. In a third container weigh out 1184 gms of Grade 20-30 Ottawa sand. This container is reusable also. In a small beaker, measure out 2.0 ml of hardener (peroxide). The beaker can be glass or plastic and can be reused. Have sufficient molds clean and ready for material placement. To aid in the release of the aggregate from the molds a release agent may be used. Add the wollastonite and silica to the resin and mix thoroughly followed by adding the hardener. Continue to mix thoroughly. Later add Grade 20-30 Ottawa sand and mix until evenly coated. Fill the molds with the mixture up to the ledge. Ensure that the mixture is off the ledge or the operator has to use sand paper to remove the excess mix to be able to fit the samples into the mold used to clamp down the specimen during testing.

After finishing preparation of part 1 components and placing the mix in the mold, the components from part 2 should be mixed and filled in rest of the mold. Similar to part 1, the components in part 2 are mixed under a well ventilated fume hood. Using another large disposable container prepare the base of coupons by combining part 2 mixture in the same order as part 1 but this time without the sand. Fill the rest of the mold with the part 2 mixture and top

with caps for the molds, pushing down firmly and not sliding back and forth. Mixture will overflow on side of mold. Leave it to harden. It is easier to remove in big chunks than if you try to clean it up now and leave a thin layer.
The part 2 mixture will only make enough for four or five molds so you will have to repeat until all molds have a second layer.

Let the samples dry in the ventilation hood for 3 hours to set the epoxy mix that is overflowing the mold. Later, place the molds in a well ventilated oven at 210˚ F oven for 1 hour. Take out and place the molds in a well ventilated hood for 12 to 16 hours to cool and finish setting. Remove the samples from the molds and prepare them for the testing.

It should be noted that a total of 12 samples can be prepared following the procedure mentioned above.

CALCULATIONS:

The polish value of the test specimens are adjusted depending on the change in the average polish value of the control specimens. The formula to be used is shown below:

$$\text{Adjusted PSV-n} = \frac{BPN_a \times BPN_{cs}}{BPN_{ct}}$$

Where:

PSV-n = Residual polished value after n hours of polishing

BPN_a = British Pendulum Tester number for the coarse aggregate sample.

BPN_{cs} = Average established British Pendulum Tester number for the control sample.

BPN_{ct} = British Pendulum Tester number for the control sample used for a particular test.

REPORT:

The initial and final polish values of the test specimens are reported to the nearest 1.0 for each aggregate source evaluated.

APPENDIX B

Proposed MSMT
Laboratory Method of Polishing Aggregates Using Aggregate Polishing Equipment

<table>
<tr><td>Recommended Approval
Team Leader Date
Regional Engineer Date</td><td colspan="2">Maryland Department of Transportation
State Highway Administration
Office of Materials Technology
MARYLAND STANDARD METHOD OF TESTS</td></tr>
<tr><td>Approved:
Deputy Chief Engineer Date</td><td>LABORATORY METHOD OF POLISHING AGGREGATES USING AGRREGATE POLISHING EQUIPMENT</td><td>MSMT XX</td></tr>
</table>

SCOPE:

The procedure is used to polish aggregate samples using the Aggregate Polishing Equipment (APE).

REFERENCE:

MSMT XX Laboratory Method of Measurement of Frictional Properties of Aggregates Using the Dynamic Friction Tester (DFT)

ASTM E1911-09 Standard Test Method for Measuring Paved Surface Frictional Properties Using the Dynamic Friction Tester

ASTM D 3319-06 Standard Practice for the Accelerated Polishing of Aggregates Using the British Wheel

Circular Track Polishing Machine, Apparatus Specification and Operation Manual, North Central SuperPave Center, Purdue University, November 2008

MATERIALS AND EQUIPMENT:

1. The APE circular track polishing machine.

2. Three patterned pneumatic tires with a tire size of 2.80/2.50 and cold tire pressure maintained at 240 ± 34 kPa (35 ± 5 psi) manufactured by Cheng Shin Company.

3. Circular “donut” shaped stainless steel mold with outside diameter of 14 inches, inside diameter of 8 inches and a height of 1 inch. The donut will slide into a rectangular stainless steel prism with a square base of 508 mm × 508 mm (20.0 × 20.0 in)

4. Resin (Isophthalic Tooling/Structure) such as Polylite® Polyester 32-773 (resilient wax-free Surfacing Resin) or equivalent material as a bonding agent (as specified in ASTM D3319 for the British Wheel).

5. Wollastonite (NYAD 400 Extender Pigment)

6. Silica (Amorphous Fumed Silica, 150 grit size)

7. Hardener (Methyl Ethyl Keyton Peroxide) as a catalyst for faster curing of the polyester resin (as specified in ASTM D3319 for the British Wheel)

8. Mold releasing agent, for example, # 2 Green Wax by Glass Supply, Inc.

9. Glass beads

10. Well ventilated oven

11. Well ventilated hood

12. Miscellaneous supplies, including disposable cups, spatula, and stirring rods.

13. At least 3.5 lbs of aggregates passing the ½ inch sieve and retained on the ⅜ inch sieve. The above specified quantity is needed to prepare one sample.

SIGNIFICANCE AND USE:

The Aggregate Polishing Equipment simulates the polishing effect of vehicular traffic.

TEST PROCEDURE:

SAMPLE PREPARATION

1. The aggregate to be used for testing should pass the ½ inch sieve and be retained on the ⅜ inch sieve. The resultant quantity should be at least 5 lb.

2. Thoroughly wash the aggregates obtained from Step 2 and dry overnight (12 to 14 hours) in the oven at a constant temperature of 110 ± 5°C (230 ± 9°F).

3. Clean the casting mold and coat the casting mold with the mold releasing agent or green wax. The casting mold is similar to Figure 1.

Figure 1. Casting mold and specimen coupon.

4. Manually place the aggregates in the stainless steel mold so the maximum surface is occupied with aggregates on the top layer of the sample. If the aggregates are flat, then select the smaller flat aggregates (with a 3-D texture), so the epoxy will adhere to it more effectively.

5. After the aggregate placement is completed, spread glass beads a quarter to half-way through from the base of the aggregate layer, so the epoxy will not seep through the aggregate layer and be exposed on the top layer, once the sample is finished.

6. Prepare the epoxy mix in a vented chamber or room as per the following quantities:

Material	**Quantity**
Wollastonite	120 gm
Silica	11 gm
Resin	296 gm
Hardener	4 gm

Note 1. Increasing wollastonite above the limit (120 gm) reduces the shrinkage, but it results in additional aggregate pop-outs, so it is not recommended.

7. In a vented chamber or room, apply the epoxy to the mold.

8. Let it air dry in a properly vented chamber or hood for 12 to 24 hours and remove the specimen from the mold once it is hardened.

9. Write the following information on the back (side that will not be polished) with a water-proof marker:

No.	Description
1	Quarry name
2	Log number
3	Specimen number
4	Date prepared
5	Contract number
6	City name/location

The final test specimen should appear similar to Figure 2.

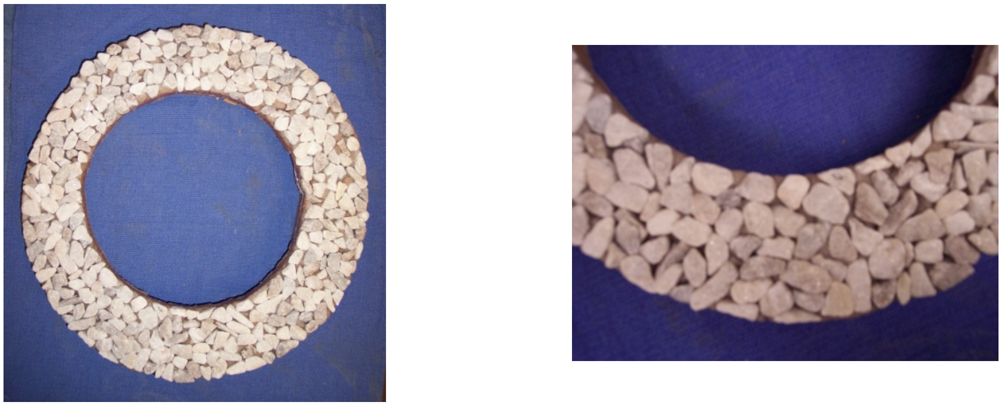

Figure 2. Example specimen ready for test.

EQUIPMENT SETUP

Prior to starting the test, the following checks shall be performed:

1. The polishing should be performed at an ambient temperature of 68 ± 4^{o}F (20 ± 2^{o}C).

2. The test shall be conducted dry. No water should be introduced during polishing.

3. The tire tread should be free of any visible contamination and if present, the tires should be cleaned using a sharp knife to gently scrape the contaminated tire while ensuring that the tire is not cut. If necessary, the tires shall be replaced. It is recommended to replace the tires when the tread depth is at the minimum acceptable depth of 2 mm or approximately half a million revolutions, whichever comes first.

4. Maintain a cold tire pressure of 240 ± 34 kPa (35 ± 5 psi) in all three wheels. Check prior to testing.

TESTING

1. Prior to polishing (0 revolution), the sample should be tested using the Dynamic Friction Tester (DFT) to obtain the initial friction value, μ_0 as per MSMT XX, Laboratory Method of Measurement of Frictional Properties of Aggregates Using the Dynamic Friction Tester (DFT).

2. After the DFT test, the specimen is placed at the base of the polisher. Position the specimen by raising the polisher using the three remotely controlled actuators. Using the three remotely controlled actuators, the polisher is gently lowered to the proper elevation. The proper elevation corresponds to the position at which the pin used to control the total force applied to the sample is located between the upper and lower bounds. Adjust the height with the APE remote control unit to properly place the wheels on the sample. Legs should be off of the ground and should return back to the base with slots provided for holding the legs.

   Warning: the legs of the APE machine may get stuck or out of order if stuck. Use appropriate tools to adjust. Do not use your hands!

1. The specimen should be positioned so that the wheels rotate on the same footprint as where the testing is performed by the DFT. In order to improve precision and expedite positioning of the specimen, the four side and two back alignments screws shall be used to adjust the location of the specimen and to hold it in the desired position during polishing.

2. Ensure that the polisher frame and the four corners of the base of the APE are equidistant.

3. Once the appropriate elevation is achieved, in order to keep the elevation height fixed, the leveling device should be secured with two mechanical nuts.

4. Lock the safety door located in front of the polisher using the safety clips.

5. Enter the number of revolutions as 100,000 into the control panel located on the upper part of the polisher. It should be noted that one revolution corresponds to one pass made by all the three wheels. It should also be noted that additional stops and DFT readings at increments up to 100,000 revolutions (e.g. 20,000, 50,000, 80,000) can be performed if desired, but this is not necessary.

   Figure 3 is a picture of the polisher in action (note: safety door not in position for demonstration purposes).

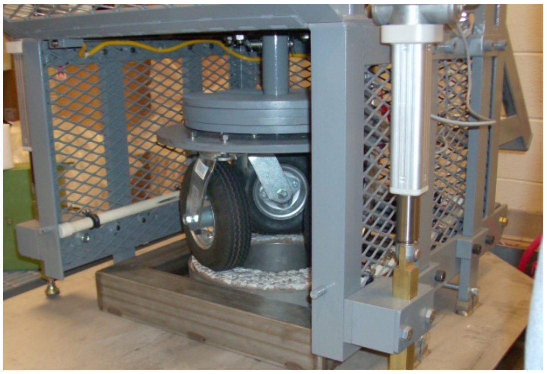

Figure 3. Picture of polisher with specimen in-place

1. After 100,000 revolutions, the polisher stops automatically and the specimen shall be removed from the polisher. The safety door is opened and securely held to prevent unexpected closure and possible injury. The side alignment screws are unscrewed.

   Ensure that the same number of rotations is applied to each screw in order to provide future correct positioning of the specimen. The leveling screws shall stay locked during this process.

2. Using the three remotely controlled actuators, the polisher is lifted and the specimen is removed from the APE.

3. The operator shall review the aggregate specimen throughout testing. If more than 20 aggregates become dislodged during testing, the test should be stopped and the testing supervisor consulted. The testing supervisor shall make a decision to either continue the testing or reject the specimen and re-test the aggregate source using a new specimen.

4. The specimen is tested for aggregate friction using DFT according to MSMT XX. This measurement is referred to as μ_{100k}.

REPORT:

No report shall result from this test procedure.

APPENDIX C

Proposed MSMT
Laboratory Method of Measurement of Frictional Properties of Aggregates Using the Dynamic Friction Tester

Recommended Approval Team Leader Date Regional Engineer Date	Maryland Department of Transportation State Highway Administration Office of Materials Technology MARYLAND STANDARD METHOD OF TESTS	
Approved: Deputy Chief Engineer Date	**LABORATORY METHOD OF MEASUREMENT OF FRICTIONAL PROPERTIES OF AGGREGATES USING THE DYNAMIC FRICTION TESTER**	**MSMT XX**

SCOPE:

The procedure is used to measure the frictional properties of aggregates as a function of speed using the Dynamic Friction Tester (DFT).

REFERENCE:

MSMT XX Laboratory Method of Polishing of Aggregates Using Automated Polishing Equipment (APE)

ASTM E1911-09 Standard Test Method for Measuring Paved Surface Frictional Properties Using the Dynamic Friction Tester

MATERIALS AND EQUIPMENT:

1. Dynamic Friction Tester (DFT) as per ASTM E1911-09.
2. Dynamic Friction Controller as per ASTM E1911-09.
3. Water Supply unit to maintain a wet condition of the test surface.
4. Synthetic Rubber Slider conforming to ASTM E1911-09.
5. Personal computer to view and store the data collected by the Dynamic Friction Tester.
6. Aggregate sample in the shape of a “donut” with an outside diameter of 14 inches, an inside diameter of 8 inches and a height of 1-inch as per MSMT XX, Laboratory Method of Polishing of Aggregates Using Aggregate Polishing Equipment.

SIGNIFICANCE AND USE:

The DFT is a portable device used for measuring the coefficient of friction, μ, of a surface as a function of sliding speed.

CALIBRATION:

The calibration procedure should be performed as instructed in ASTM E1911 and as per manufacturer's specifications.

TEST PROCEDURE:

1. Ensure that the rubber sliders being used were manufactured less than 12 months prior to the test. The rubber sliders should be replaced prior to testing a specimen. A maximum of twelve DFT tests should be conducted with a set of sliders.

2. If necessary, use a foxtail to clean the area under test.

3. Pour clear water on the sample to make sure it is properly wet and a thin water lining is on the top of the sample, i.e. make sure the sample is submerged under a thin line of water (approximately 2 mm below).

4. Carefully lift the DFT (Dynamic Friction Tester) and place it on the sample mold. It should sit on the mold equidistant from each direction (or the feet of the DFT should be placed on the 4 circular markings on the mold).

5. Fill the DFT's water cylinder with clear water and open the flow valve on the side of the tank to make sure water flows freely. You may have to lift up the hose above the water container to remove the air bubble or else the water may not flow properly. IT IS ESSENTIAL THAT THE WATER CYCLINDER BE PLACED AT EXACTLY 2 FEET ABOVE THE DFT. The DFT controller should be set to automatic for water flow.

6. Attach the female end of the water hose to the male end of the DFT.

7. Attach the power cables from the controller to the DFT and make sure proper female ends match the corresponding male ends. Battery connection – makes sure it's off the floor and away from water and keep it charging when it's not in use.

8. Attach the battery to the DFT controller with the corresponding cord ends.

9. Flip the switch "On" on the DFT controller and wait for the menu to appear. It may take a few seconds. Once the menu is set up, select the "Measurement option".

10. Use the designated arrow key to change the name of the testing.

11. Select auto run and speed desired (80 km/hr). Use proper ear protection while running the DFT.

12. Take the readings for four runs.

13. Transfer the data from the DFT controller to the PC by following these steps[1]:
    a. Click on Data Received (F9).
    b. Click on Connection.
    c. Within 10 seconds click on Transfer to Measurement Data and click "OK/Go".
    d. Now click on Start Transfer (F1).
    e. Within 10 seconds click on "Go" (this timing is critical for proper data transfer).

REPORT:

The following data should be reported:

1. Quarry name

2. City name/location

3. SHA log number

4. Specimen identification number

5. Contract number

6. Date of production of rubber sliders, MM/DD/YYYY

7. Rubber slider replacement date

8. Date of most recent DFT calibration, MM/DD/YYYY

9. Data to be recorded for each DFT test
    a. Test date, MM/DD/YYYY format
    b. Operator name
    c. Number of revolutions of APE device, whole number
    d. Name of raw data files (four per test)
    e. Four readings of the DFT friction numbers (μ) at individual speeds of 20, 40, and 60 km/h (12.5, 25, and 37.5 mph), to two decimals
    f. Friction-speed curve for each test result

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[1] If there are any problems with the data transfer, turn off the DFT controller and restart data transfer. If DFT memory becomes full, data transfer problems usually result. Therefore, download data from the controller after every set of DFT test results for a given stop (nominally every four tests). Also for most of the problems related to the DFT or the DFT controller, please refer to the "D. F. Tester Instruction Manual".

DATA COLLECTION FORM:

1. Quarry Name: ______________________
2. Quarry City Name/Location: ______________________
3. SHA Log Number: ______________________
4. Specimen ID Number: ______________________
5. Contract Number: ______________________
6. Date of Production of Rubber Sliders: __ __/__ __/__ __ __ __
7. DFT Calibration Date: __ __/__ __/__ __ __ __
8. DFT Results (attach friction/speed graphs):

Date of Test	__ __/__ __/__ __ __ __				
Operator Name	________________________________				
APE Revs	__ __ __ , __ __ __				
Test	1	2	3	4	Average
File Name	________ . __	________ . __	________ . __	________ . __	
DFT - 20 km/h	0.__ __	0.__ __	0.__ __	0.__ __	0.__ __
DFT - 40 km/h	0.__ __	0.__ __	0.__ __	0.__ __	0.__ __
DFT - 60 km/h	0.__ __	0.__ __	0.__ __	0.__ __	0.__ __

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Note: For a complete bibliography of material used in this study, please reference "Aggregate Friction State of the Practice Review," May 1, 2006.