IDENTIFICATION OF LABORATORY TECHNIQUES TO OPTIMIZE SUPERPAVE HMA SURFACE FRICTION CHARACTERISTICS

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16. Abstract

This report summarizes an investigation into various options for polishing, testing and analyzing pavement surface frictional properties in the laboratory. Devices were sought that could assess the effects of both microtexture and macrotexture of hot mix asphalt surfaces in the laboratory and the field. The investigation consisted of a detailed literature review and consultations with users of existing devices for polishing and testing pavement materials. The recommended devices include the Dynamic Friction Tester (DFT) and the Circular Texture Meter (CTM). This study is the first phase of a planned three-phase research program to examine the frictional characteristics of Superpave HMA mixtures. A plan for continuing with Phase II of the project, using the recommended devices and funded by the Indiana and Iowa Departments of Transportation, is also outlined.

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Introduction

This report summarizes an investigation into various options for polishing, testing and analyzing pavement surface frictional properties in the laboratory. The investigation consisted of a detailed literature review and consultations with users of existing devices for polishing and testing pavement materials. This study is the first phase of a planned three-phase research program to examine the frictional characteristics of Superpave HMA mixtures. A plan for continuing with Phase II of the project, using pooled funds contributed by the Indiana and Iowa Departments of Transportation, is also outlined.

Background

Pavement friction arises from two primary features of the surface. The microtexture is largely a function of the surface texture of the aggregate particles. Sandstone, for example, has a rougher surface texture and provides more friction than a smooth limestone. Different aggregates also vary in their tendency to lose microtexture, that is to polish or become smoother, under the abrasion of traffic. The macrotexture, on the other hand, is determined by the overall properties and texture of the pavement surface. Pavement macrotexture can be increased by designing pavement surfaces with greater texture depth, by changing the sizes and distribution of sizes of the aggregates. Microtexture can only be changed by changing the types of aggregates used in the mixture.

Most state specifications for bituminous pavement surface courses attempt to ensure adequate friction is provided for various traffic levels by limiting the types of aggregates that can be used; that is, by controlling the microtexture. Controlling the quality of the coarse aggregates is the most common approach (*1*). High quality friction aggregates are specified for high traffic volume situations. This can, however, be an expensive option, since high friction aggregates may not be readily available and may have to be transported from a distance.

Tests relating to surface friction used during mix design in most states evaluate only the aggregates, not the frictional properties of the pavement surface (*1*). In other words, the test methods focus on microtexture rather than macrotexture. These test methods, then, cannot adequately assess the pavement friction provided by the combination of micro- and macrotexture of a mixture.

Field friction testing can provide data on the pavement micro- and macrotexture, but requires the construction of sizeable and expensive pavement sections for testing. Field friction testing, then, is typically used only to assess the level of friction on in-service pavements at a given point in time. It is not feasible to accelerate polishing on full-scale field sections to develop curves showing the decline in friction over time.

Changes in the pavement macrotexture may affect other properties, such as noise generation, as well as friction. Noise is a growing concern, especially in urban areas. Open-graded mixtures have been demonstrated to reduce tire-pavement noise and are widely used in Europe for that purpose. These open, or porous, mixtures may also provide superior frictional properties and reduced splash and spray. Relatively dense graded mixtures with favorable macrotexture may possibly demonstrate some noise reduction compared to conventional dense mixtures. Other mixture properties that may change with changes in the aggregate structure include strength, durability and cracking resistance.

Some work has been done to develop laboratory methods to polish specimens, test their surface friction and predict changes in friction over time. New technologies for characterizing surfaces, such as laser imaging, may also prove useful for predicting surface frictional properties. These existing methods and new technologies should be evaluated to determine their applicability to predicting the frictional properties of Superpave and other mixtures in the field. Test methods for measuring and predicting surface friction should also be applicable to porous mixtures and other pavement materials.

Given a test method to estimate pavement friction, various combinations of aggregates with different gradations can be evaluated to determine the effects of the combination of micro- and macrotexture. This will be the focus of a two-phase follow-up to this study.

Problem Statement

There is a need to assess and optimize the combined effects of pavement micro- and macrotexture provided by Superpave mixtures to maintain the current level of pavement friction. In order to achieve that optimization in a timely fashion, it is necessary first to identify an accelerated method to polish samples and test their frictional properties, as will be described in this report. Blends of aggregates should also be evaluated to determine how changes in the aggregate blend affect other mixture properties, including noise generation, strength (or stiffness) and cracking resistance. This will be accomplished in a follow-up study funded by the Indiana and Iowa Departments of Transportation.

Objectives

The objective of this study is to identify an accelerated method or methods for polishing or abrading samples and measuring their surface friction characteristics. The test(s) could be used by any agency to evaluate various surfacing materials, although the primary focus of this project will be on hot mix asphalt surfaces in the Midwest. The test(s) would also be applicable to porous mixtures and other surface types designed to provide safe, quiet roadway surfaces.

This study will be followed by a laboratory and field evaluation. The objective of that research will be to evaluate various blends of aggregates to optimize the combination of micro- and macrotexture to achieve a desired level of friction. Aggregate classifications and properties currently used to provide desirable friction levels for high traffic situations will be evaluated and possibly revised based upon this research. (These aggregates will be referred to here as “high friction aggregates” as opposed to “common aggregates,” which can be used in lower traffic volume situations.) The goal will be to maintain the currently provided level of friction while reducing the reliance on the microtexture provided by special friction aggregates, if possible, by increasing the mixture macrotexture.

As a final objective of the follow-up study, other properties of the various mixtures evaluated will be assessed to determine if changes in the micro- and macrotexture have a positive or negative effect on those other properties. Properties to consider include strength (stiffness), resistance to cracking and possibly noise generation.

Work Plan

The goals of this research project will be addressed through a coordinated research effort involving three phases, broken into seven primary tasks. The tasks below are as written in the original proposal. This report will focus on the results of Phase I, but will also outline the proposed research to be conducted under Phases II and III.

Phase I consists of an evaluation of existing devices and established new technologies for accelerating polishing and measuring surface friction properties and is summarized here. Phase II involves developing an experimental design matrix for evaluating various combinations of aggregates and mixture types using the device(s) selected in Phase I. (A preliminary plan is presented here.) A statistically valid, representative portion of the testing matrix will be conducted during Phase II. The remainder of the experimental design will be completed in Phase III, which will conclude the program of research.

Phase I

Task 1 – Literature Search

A detailed review of the literature pertaining to laboratory testing of friction will be conducted, starting with a search of the Transportation Research Information Service (TRIS) database. This literature review will help to identify potential test procedures and new technologies to evaluate in Task 2.

Task 2 – Compare Devices

Various devices and laboratory procedures for accelerating wear (polishing) and for evaluating surface friction of mixtures will be compared in terms of performance history (if available), ability to discern changes in both pavement micro- and macrotexture, and ability to identify mixtures with superior frictional properties. Devices to be evaluated will be identified in Task 1 and through contacts with other researchers in the field. The devices/procedures will include such devices as the laboratory polishing and friction testing devices used in Michigan, topographic characterization of the surface by scanning laser and x-ray tomography.

Reviewing the literature, conferring with users of the technology and, if possible, evaluating a few standard specimens in various devices will all be used to compare and contrast the technologies. Laboratories utilizing the tests may be visited to observe testing in progress and thoroughly review the procedures.

At the conclusion of Task 2, the research team will prepare a written report for the study advisory committee to review the findings to date. A decision will be made jointly on which device(s) to further evaluate in Phase II. Depending on the technology chosen for further evaluation, a decision will also be made regarding procurement of the device(s) or testing services. Possible options include building the device, contracting with another lab to perform needed tests, borrowing the device(s) from another lab or the vendor, or a combination of the above. Funding is earmarked in the budget for this equipment or testing service, but there is no allowance in the time schedule for any significant fabrication time, if required.

Phase II

Task 3 – Develop Experimental Design
A detailed, statistically sound experimental design will be formulated to guide the subsequent research efforts. The statistical consultant will advise on the ultimate final experimental design and the sequence of testing. The design will be divided into two phases in a statistically sound manner to allow for mid-course review of the findings to be made at the conclusion of Phase II. The Phase II results will be reviewed in consultation with the study advisory committee to allow for modifications in the testing program to be implemented in Phase III. The statistical consultant will advise on the best partitioning of the research effort into Phases II and III to ensure the statistical validity of the analysis of the results. Detailed test procedures will also be developed to ensure consistency in sample preparation and testing throughout the project.

The initial experimental design includes five variables.

Gradation – Three aggregate gradations, fine, coarse and s-shaped gradations.
Aggregate Size – Two aggregate maximum sizes, 19 and 9.5 mm (3/4 and 3/8 in)
High Friction Aggregate – Two typical friction aggregates, such as slag, quartzite or sandstone.
Common Aggregate – Three typical soft aggregates; including, for example, limestone or dolomite.
Friction Aggregate Content – Four percentages of friction aggregate, 10, 20, 30 and 40%.

Two replicates in each cell would require testing 288 specimens. Due to the comprehensive nature of the proposed research, completing this full factorial design would be a massive effort. The statistical consultant can advise on designing a partial factorial experiment that would still allow the determination of statistically sound findings.

Task 4 – Define Baseline
The existing typical friction levels provided on highways in the participating states will be established as the baseline. Any changes proposed in specifications, aggregate types or pavement surfaces as a result of this research should provide at least the current baseline friction level. Samples of typical pavement materials that provide the current level of friction will be polished and tested using the candidate test method(s). Samples to be tested may include both pavement cores and laboratory fabricated specimens. All combinations of aggregates and mixture types, as detailed in the experimental design, will be compared to this baseline.

Task 5 – Run Phase II Experimental Program
The Phase II portion of the testing program designed in Task 3 will be conducted. The initial testing is likely to involve testing approximately 48 specimens, or one-sixth of the complete testing matrix as currently envisioned. Testing will include basic material characterization, accelerated polishing and friction testing, and evaluation of mixture stiffness and cracking resistance.

Each material and mixture to be evaluated will be characterized in basic material terms. For example, the aggregates will be evaluated in terms of fine aggregate angularity, coarse aggregate angularity, petrographic classification, hardness, etc. Mixtures will be analyzed for density, void content, strength or stiffness, cracking resistance and other properties of interest. Strength and cracking resistance will be analyzed using the shear tests, proposed Superpave simple performance tests and indirect tensile tests.

In addition to material characterization, replicate samples will be subjected to accelerated polishing and friction testing using the device(s) selected in Phase I.

Task 6 – Interim Report
The results of the testing conducted in Phase II will be analyzed and an interim report will be prepared. Statistical analysis procedures will be used as appropriate. The Phase II results will be reviewed by the study advisory committee and possible modifications to the experimental design will be discussed before commencing Phase III.

Phase III
Task 7 – Complete Experimental Program
Following discussions with the study advisory committee and incorporating recommended revisions to the experimental program, the remaining cells in the experimental matrix will be filled. Material characterizations, strength testing and cracking analyses will also be conducted as needed and as in Task 5 above.

Task 7 will also include noise testing on selected aggregate and mixture combinations. The facilities of the Institute for Safe, Quiet and Durable Highways will be used to test six to twelve selected mixtures for noise properties under a full size test tire. The mixtures to be tested will be determined in consultation with the study advisory committee.

Task 8 – Prepare Final Report
A final report summarizing the entire research program will be completed. The draft report will be reviewed by the study advisory committee and subsequently revised.

Phase I Findings

The purpose of this report is to summarize the findings of Phase I and outline the recommended approach to Phases II and III.

Literature Review and Discussion

There is an extensive amount of literature relating to pavement friction, its measurement and prediction. Highlights of the review of this literature, particularly as they pertain to the objectives of this project, are summarized here.

General Background

It is a well-known fact that field friction numbers show seasonal and short-term variations. The seasonal variations yield a cycle with lower friction levels typically occurring in Summer and Fall and higher friction levels in Winter and Spring. This cycle is typically attributed to clogging of the surface during the dry months and a rejuvenation of the surface through the abrasion of traffic during the cooler months of the year. Interposed over this seasonal variation are short-term variations due to local rain events and temperature fluctuations (*2*). These fluctuations have complicated attempts to correlate laboratory predictions of friction with actual field tests, when such correlations have been attempted.

It is also well known that pavement friction depends on both the microtexture of the aggregates themselves and the macrotexture of the overall pavement surface. Microtexture is usually defined as small-scale texture up to about 0.5 mm (0.02 in), and macrotexture is larger texture between about 0.5 and 15 mm (0.02 – 0.59 in) (*3*, *4*). For wet pavement friction, macrotexture helps to provide drainage channels for water to escape, and microtexture breaks the last thin film of water coating the aggregate particles to allow aggregate-tire contact (*4*). Microtexture has an effect on friction at all speeds, but macrotexture assumes a greater role at speeds of 64 kph (40 mph) or higher (*2*). Kennedy (*3*) said that microtexture predominates at speeds up to only 50 kph (31 mph). Macrotexture is the controlling factor in the speed dependency of friction. In other words, the microtexture controls the friction level at low speeds, and the macrotexture controls how the friction changes with increasing speed (*3*).

Yager and Bühlmann (*5*) investigated the role of pavement macrotexture in draining airport runways. They note that macrotexture is very important, but add that macrotexture alone cannot define the frictional properties of a pavement. It is important to assess both the macrotexture and the microtexture. Kulakowski and Harwood (*6*) emphasized the importance of macrotexture by reporting that as little as 0.025 to 0.23 mm (0.001 to 0.009 in) of water on the surface can lead to a significant reduction in friction on the order of 20-30% of the dry friction.

Dames (*7*) observed that frictional resistance depends not only on the mineralogical properties of the aggregate but also on the grain size and distribution, or the surface texture. Dames also noted that the influence of the sand fraction in the overall gradation may be more significant than previously thought.

Kandhal and Parker noted that, because of the complexities and many interrelated factors involved in frictional resistance of an asphalt pavement, "a test that measures only the microtexture of the coarse aggregate may not be an efficient means of evaluating suitability for polish and friction resistance" (*8*).

Jayawickrama et al. (*1*) also noted the importance of assessing both micro- and macrotexture. They stated that an ideal design system should account for differences in both pavement qualities.

Doty (*9*) reported in a comparison of friction to surface texture, as measured by the sand patch test and outflow meter, that there was a general trend of higher friction with increasing texture depth for a variety of surface types including open and dense graded asphalt, sealed surfaces and polished and grooved PCC. Surface texture alone, however, did not yield strong enough relationships to establish a minimum texture depth criterion for use as a specification limit.

Many researchers have expended considerable effort attempting to correlate one measurement, typically aggregate microtexture, to pavement friction using statistical regressions with traffic and other factors (*10*, *11*), spectral power densities of the surface (*12*, *13*), and even fuzzy-set mathematics (*14*). Prasanna (*15*) pointed out that correlations can be improved by relying on more than one measured parameter and developed a software program for Texas that utilizes different regression equations depending on the predominant aggregate type.

These sources and others show that assessing pavement friction requires measurement of both macrotexture and microtexture. Focusing on one measurement alone will overlook the contributions of the other type of texture. To meet the objectives of this research project, a test method or set of tests sensitive to both types of texture is required in order to assess how increasing the pavement macrotexture can perhaps reduce the reliance on aggregate microtexture.

The remainder of this literature review focuses on particular test methods or procedures used to assess frictional properties, polishing of aggregates and surface texture. The suitability of the various devices for this research is also discussed. Test methods that rely solely on properties of the aggregates without polishing, such as acid insoluble residue or the Tennessee terminal texture condition method (T^3CM) (*16*), are not discussed since they clearly cannot be used to assess macrotexture effects. A chart showing the advantages and disadvantages of the various devices evaluated is shown in Appendix A.

Devices for the Accelerated Polishing of Aggregates and Mixes

There are several types of devices designed to accelerate polishing of aggregates and mixtures.

British Polishing Wheel. The aggregate polishing devices, typically polishing wheels, work by reducing the microtexture of the aggregate. In the British Polishing Wheel, curved specimens are clamped to the outside of a wheel assembly forming a continuous surface of aggregate particles. The wheel is then rotated against a rubber-tired wheel that performs the polishing action. An abrasive grit is fed between the wheel and specimens to help accelerate the polishing (*17*). The specimens are formed by mounting uniformly-sized coarse aggregate particles by hand in a curved mold and holding them in place with a bonding agent (polyester or epoxy resin) (*18*).

The device is bench scaled and could be easily accommodated in most laboratories. It does require a means of feeding and draining the water and grit to the tire-aggregate interface. The companion British pendulum is also small and portable.

The British polishing wheel is used for aggregate coupons only, however, not actual pavement samples, making it inappropriate for meeting the objectives of this research effort. In addition, the method evaluates only loss of microtexture of the coarse aggregate fraction, neglecting any contributions of the fine aggregate or the macrotexture.

Penn State Reciprocating Polishing Machine. The Penn State Reciprocating Polishing Machine represents another style of polishing machine. This machine can be used in a laboratory or in the field to polish aggregates or mixes. A 90 by 140 mm (3.5 by 5.5 in) rubber pad oscillates back and forth across the specimen while an abrasive slurry is sprayed on the interface (*19, 20*). The device is bench sized and polishes an area not less than 100 by 165 mm (4.5 by 6.5 in), but like the British wheel it also requires water.

While this device can be used with both aggregates and mixtures, the polishing action affects the aggregate microtexture, which is then assessed using the British pendulum, described later. The slider moves backward and forward obliterating any possible directional effects of the polishing, but increasing the speed of polishing. This device was never widely used, and its ASTM specification was discontinued in 1997.

Circular Track Polishing Machines. Circular track polishing machines represent another type of polishing machine, some of which can be used for both aggregate and mixture specimens.

The North Carolina State University (NCSU) Wear and Polishing Machine utilizes four individually mounted, free rolling wheel assemblies that pivot about a central shaft. This device can be used without the aid of grinding compounds to polish both aggregates and mixes. The wheels are normally loaded to 320 N (72 lbf), but additional weights can be added to increase the loading and polishing for concrete specimens. The tires are 279 mm (11 in) diameter, smooth nylon tires. Twelve specimens are arranged around the perimeter of the track for polishing. The overall diameter of the track, to the center of the polishing wheels, is 914 mm (36 in). After polishing, which typically takes about 8 hours, the friction can be measured using either the British pendulum (for low macrotexture specimens) or the Variable Speed Friction Tester (VST) for any specimens (*21*).

The device is fairly large, but not excessively so. It is an advantage that no slurry or water must be provided or drained.

The circular track polishing machine is evidently still in use since the ASTM standard was reapproved in 2002, however, neither North Carolina State University, which developed the device, nor the North Carolina DOT reported using it when contacted as a part of this literature review.

NCAT has developed a slightly smaller version of a circular polishing machine that is not currently covered by any ASTM or AASHTO standard. Their device is sized specifically for later testing using the Dynamic Friction Tester and Circular Texture Meter, both of which are covered by ASTM standards as described later. The NCAT polishing machine uses three pneumatic tires 203 mm (8 in) in diameter to polish a nominal 500 mm (20 in) square slab. Resin or hard tires have also been used. With rubber tires, water is used to wash abraded rubber particles off the surface during polishing. Weights are applied to produce a total dead weight of 68 kg (150 lbf) through the three wheels. As with other polishing devices, polishing can be stopped periodically to allow measurements to be taken. Up to 100,000 revolutions at 40 rpm (41.7 hours) have been applied to reach terminal polish, but that many passes are rarely needed depending on the aggregate and the purpose of the testing.

NCAT uses a modified linear compactor, such as that used to compact APA specimens, to produce the slabs for testing. They increased the size of the form and the vertical compacting plates to fabricate the larger slabs. While a local machine shop could make the modifications, it was fairly costly.

The NCAT device is relatively small, but does require water for operation. Its operation is very similar to that of the NCSU device.

While this device has not been correlated to traffic or other field conditions, neither have the other polishing methods. NCAT's experience shows that the device does polish the pavement slabs to a terminal value. In their development work, they experimented with different speeds, tire types, methods of cleaning the surface, etc., and have found the method summarized here quite satisfactory.

Michigan Wear Track. Michigan DOT uses a concept similar to the circular tracks above, but on a larger scale. They developed a wear track in 1971 that uses full-scale smooth friction test tires to polish coarse aggregate specimens, which are later tested using a laboratory version of the ASTM towed friction tester, described later. The circular wear track is very large, with a diameter of 2.13 m (7 ft). It accommodates 16 trapezoidal specimens. The individual specimens have parallel sides of 394 and 495 mm (15.5 and 19.5 in) and non-parallel sides of 279 mm (11 in). Two wheels with normal forces of 3.6 kN (800 lbs) pivot around the center (*4*).

Though this device seems to be the closest to real-world conditions, it is also used for polishing coarse aggregates only, not pavement samples. It is by far the largest polishing device found and requires a significant commitment of laboratory space and resources.

Sample preparation is time-consuming. Uniformly graded coarse aggregates are placed in steel molds over a retarding compound, then portland cement mortar is added to hold the aggregates in place. After a 24-hr cure, the paste is removed from around the aggregates on the test face by scrubbing. This is followed by seven days of wet cure and 14 days of air curing prior to polishing. The polishing itself takes about four million wheel passes (*4*). At selected intervals during polishing, the samples are removed from the wear track and tested in the laboratory friction tester, described later.

Summary and Discussion. The British polishing wheel and Michigan wear track polish coarse aggregate samples only, so they are not appropriate for evaluating both aggregate microtexture and mixture macrotexture as needed in this study.

The Penn State reciprocating device moves backward and forward over the test specimen, so its polishing action would not reflect any possible directional polishing under traffic, which typically moves in one direction only over a given pavement surface. Due to its reliance on microtexture only and its current state of disuse, this method is not a good candidate for this research.

The selection of an appropriate polishing device also depends on the nature of the measurements that will be conducted during and after polishing. So, whether the test specimen should be linear, as with the Penn State device, or circular, as with the NCAT circular polisher, or a segment from a circle, as with the NCSU device, depends on how the friction testing is to be done. Of the devices that can be used to test pavement samples, the circular polishing devices seem most promising, but the final selection cannot be made without considering the friction testing, as described in the next section.

Friction Measurement

There are a variety of devices that have been used to assess friction. These are summarized and discussed in the following section.

Pendulum Devices. One of the most widely used methods is the British pendulum device, which can be used on the curved coupons from the polishing wheel, on flat specimens from a circular polishing track or reciprocating polisher, or on actual roadway surfaces. The British Pendulum

Tester consists of a rubber slider attached to the end of a pendulum arm. As the pendulum swings, it is propelled over the surface of the specimen. As the rubber slider contacts the surface of the specimen, the kinetic energy of the pendulum decreases due to friction. This energy loss is measured and reported as the British pendulum number (BPN) on flat surfaces or the polished stone value (PSV) for curved aggregate coupons from the polishing wheel (*17*). The slider travels at roughly 10 km/h (6 mph), so is only capable of measuring low speed friction (*22*).

Due to the small size of the rubber slider and its slow speed, however, it is widely recognized as a measure of the microtexture only (*17*). The benefits of higher macrotexture cannot be evaluated. In fact, the pendulum is not recommended for use in the field on surfaces with high macrotexture (*21*).

There are a number of problems with this test. Inconsistencies between different British pendulums when measuring the same surface or with the same pendulum over time have been noted. Kulakowski et al. (*23*) attributed these discrepancies to the cumbersome calibration procedure. Because the calibration was difficult to perform, they maintained, most operators were not calibrating their pendulums. A closed-loop calibration procedure was developed to correct this problem (*23*), but has not been incorporated in the ASTM standard, so is not widely used.

Smith and Fager (*24*) also noted problems with the test results caused by aggregate orientation in the coupons and perhaps other more subtle effects. Chat has been used extensively in Kansas and is generally recognized as providing good frictional properties, but it did not compare well to other aggregate types when tested in the British polishing wheel and pendulum. Smith and Fager attributed this to the fact that the flat and elongated chat particles tended to lie flat in the polishing coupons, producing a smooth test surface. In the field, a more random orientation would occur.

A somewhat minor problem involves the number of tests required. Since the slider is very small, a large number of tests is needed to obtain a representative value (*3*). The individual measurements are not time consuming, but five swings are required at each test location (*17*) and multiple test locations are needed to provide good results (*3*).

The North Carolina State University Variable-Speed Friction Tester is another pendulum-type tester. Instead of a rubber slider there is a locked-wheel smooth rubber tire at the end of the pendulum. A stream of water is sprayed at a specific velocity in the path of contact of the wheel. By adjusting the velocity of the water stream, different vehicle speeds can be simulated in the lab or in the field. However, uneven pavement surfaces in the field may provide inaccurate measurements (*25*).

<u>Michigan Laboratory Friction Tester</u>. As a companion to the wear track, the Michigan DOT uses a laboratory scale version of a towed friction trailer to measure the frictional resistance of samples polished on the wear track. The device consists of a tire in a stationary frame that is rotated at the equivalent of 40 mph then is dropped onto a specimen clamped onto the frame under a spray of water. The torque produced as the tire slows due to friction with the specimen is measured, and the peak torque is used as an indicator of the surface friction of the specimen (*4*).

Michigan uses the Average Wear Index (AWI), or change in frictional resistance with polishing, to select aggregates for surface courses. Although there is a lot of scatter in the data when attempting to correlate field friction numbers to AWI for various traffic levels, Michigan feels they have enough field history and knowledge of their aggregates to establish acceptable specification limits for AWI for different levels of traffic (*4*). Without this field performance it would be difficult to establish a good correlation due to the variability in the test data. Michigan has been working with this method since 1971. It would be hard to implement this method without investing a significant amount of time in establishing field and laboratory correlations for local aggregates.

Aside from the need for a good historical background, a major problem with this method for the purposes of this study is that it is used on uniformly sized coarse aggregate only. It provides no assessment of macrotexture effects, and there is no history of using it for pavement samples instead of aggregates only.

<u>Dynamic Friction Tester</u>

The Dynamic Friction Tester (DFT) is a portable device that allows direct measurement of the surface friction of a variety of surfaces, including pavements. The DFT consists of a horizontal spinning disk fitted with three spring-loaded rubber sliders that contact the paved surface. The standard sliders are made of the same type of rubber used in friction test tires, though other materials are available for other applications. The disk rotates at tangential velocities up to 80 kph (55 mph). Water flows over the surface being tested, so wet friction is measured as done with the towed friction trailer. The rotating disk is then dropped onto the wet surface and the friction is continuously measured as the disk slows. This continuous measurement allows determination of the speed dependency of the surface friction (*26, 27*). The DFT is affected by both the microtexture and macrotexture of the surface. When used with the Mean Profile Depth, the DFT can be used to determine the International Friction Index (*26, 28*).

The DFT is relatively small, approximately 511 mm (20.1 in) square and weighing about 11 kg (24 lbs). The tested area is a circular path with a diameter of about 284 mm (11.2 in) (*29*). A small tank is used to provide water and a personal computer is used for control of the test and data acquisition (*27*).

The tests are very quick, taking at most a couple of minutes per site. This allows testing at a large number of sites, if desired. Data analysis is also very rapid, providing essentially instantaneous readouts of friction numbers (*27*). The testing and data analysis are standardized under ASTM E 1911-98, which also describes the calibration of the friction force transducer, vertical force and tangential speed. As another positive factor, in comparisons between field friction testing devices at annual NASA Friction Workshops, DFT results correlated closely with BPN values, but the BPN values were much more variable than the DFT results (*22*).

<u>PTI Friction Tester</u>

Along with the Penn State Reciprocating Polishing Machine, the Pennsylvania Transportation Institute (PTI) also developed a companion friction tester. The PTI friction tester used a free-falling weight to propel a rubber slider in a linear path along a surface. The frictional resistance was determined from the speed of the slider across the surface. A surface with higher friction would slow the slider more than a smooth surface. Kulakowski and Harwood (*6*) used this device in their investigation of the effect of a water film on friction.

Like the reciprocating polisher, however, this device is no longer used. Due to its limited history, few citations in the literature and its current lack of use, this device will not be considered further here.

Summary and Discussion. Pendulum devices, then, have been used extensively, but they are not suitable for addressing the objectives of this project because they test microtexture and not macrotexture. The Michigan Laboratory Friction Tester seems to be as close to real-world testing as possible, but is larger, more expensive and less portable than other devices. In addition, there is no history of using this device to test mixture samples, only uniformly-sized coarse aggregate. It seems it would be possible use this equipment on mixture samples, but a significant amount of development work and analysis would be needed. The PTI Friction Tester has fallen into disfavor and is no longer used.

The DFT is worthy of additional consideration, as it appears well suited to meeting the objectives of this research effort. It is influenced by both microtexture and macrotexture. It is portable and can be used both in the lab and the field, which would allow establishing a baseline of existing pavement friction. No further developmental work is required since it is commercially available and an ASTM standard exists to standardize the testing and calibration.

Texture Measurement

Though not an explicit factor in the original plan of study, the need to be able to characterize the texture of the mix and pavement samples tested is a logical extension. The importance of the pavement texture was reinforced by the literature review. There are a variety of ways to measure pavement texture, ranging from simple, indirect estimates to extremely high tech direct measurements. Technological advances make direct measurement more feasible now than in the recent past.

<u>Volumetric Methods</u>

The sand patch method is the oldest and most common way to measure pavement surface texture. It is standardized in ASTM E965. The method consists of spreading a fixed volume of dry Ottawa sand or glass spheres over the surface and working them into the surface texture in a circular pattern. The sand should be spread until it is flush with the tops of any surface asperities. The area covered by the sand and the known volume of sand allow calculation of the average texture depth, called the mean texture depth (MTD) (*30, 31, 32*). The standard requires taking four measurements at random locations on each surface type evaluated.

The method and equipment are simple, but significant variability (poor repeatability) in the measurements has been reported (*5*). In addition, only an average texture depth can be obtained. No further analysis of the nature of that texture depth can be accomplished.

Another volumetric measure of texture is the grease patch method developed by NASA. This method is similar in concept to the sand patch, except that grease is spread over the surface in a rectangular area between parallel strips of masking tape. Again, the average texture depth is determined by dividing the known volume of grease by the area covered. The results can be skewed if grease is left on the squeegee or masking tape (*5*).

A third volumetric approach uses the same concept of spreading a known volume of material over a measured area. In the silicone putty, or Silly Putty, method, a fixed amount of putty is pressed onto the surface using a plastic disk with a round recess whose volume equals that of the putty. (In other words, the putty will completely fill the recess when pressed onto a flat surface.) When pressed onto a surface with texture, the amount of texture is indicated by the diameter of the putty (*5*).

<u>Outflow Meter</u>

The outflow meter uses the rate of flow of water to estimate surface texture. A cylinder is placed on the pavement. A rubber ring around the cylinder is supposed to meet the pavement surface as would a tire. The cylinder is filled with water, and the time for a known volume of water to escape from the cylinder through the voids and channels on the pavement surface is measured. The concept is that water will flow faster if the pavement has a rough texture than if the pavement has a smooth texture that "seals" better to the rubber ring. There are at least two versions of the outflow meter, with one developed by FHWA having the greatest use in this country (*5*).

As with the volumetric devices, the outflow meter gives an average value for the pavement, but cannot give any additional information about the distribution or nature of the texture. In addition, permeability of the pavement layer can help drain water faster. On open graded friction courses and other open mixtures, the water drains almost immediately. While permeability may be a beneficial factor in wet weather frictional resistance, as well as reduced splash and spray, it is not simply surface texture; it is porosity below the surface. For the outflow meter to truly give an indication of *surface* texture, the water must drain between the bottom of the rubber gasket and the top of the pavement layer (*5, 22*).

Stylus Devices

In the past, some researchers attempted to use a small stylus or pointer to contact the pavement surface and trace the profile. This is analogous to a profilograph, but on a smaller scale. These devices could be automated, but were still fairly limited in their ability to measure fine detail over a large area. They measured the profile in a single linear track. Repeat measurements were used to analyze additional areas.

Two examples were noted in the literature. The Surtronix 3+ profilometer has horizontal and vertical resolution of 1 μm and 0.001 μm, respectively (*13*). The Dromometer is another type of profiling device. Using a tracing pin, the Dromometer could record up to 8 inches of profile data (*12*).

These devices have been superseded by technological advances that make it possible to measure texture over a larger area more rapidly and with better resolution.

Laser-Based Devices

Technological advances in lasers and portable computers have made it possible to rapidly measure surface texture. There are even devices that can measure macrotexture at highway speeds for project or network-level investigations (*22*). A stationary device is needed for the laboratory portion of this research project.

One readily available laser-based device is the Circular Track Meter (CTMeter or CTM). The CTM, as described in ASTM E-2157(01), uses a charge coupled device (CCD) laser displacement sensor to measure the surface profile. The laser sensor is mounted on an arm that rotates around a central point at a fixed distance above the pavement and measures the change in elevation of points on the surface. The laser spot size is 70 μm (2.76×10^{-3} in) and the vertical resolution is 3 μm (0.12×10^{-3} in). Each test takes about 40-45 seconds (*22, 29*).

The CTM is a companion to the DFT and measures the texture in the same path where the DFT measures the friction. Like the DFT, it is lightweight and portable (13 kg (28.6 lbs)) (*29*). The CTM can be used in the lab or the field to measure the surface texture of pavements. Abe et al. found the mean profile depth, measured by the CTM, to be highly correlated to the mean texture depth, determined using various volumetric methods, and to the outflow time on non-porous pavements (*34*).

The CTM collects data around the circumference of a circle 284 mm (11.2 in) in diameter. The data can be separated into eight arcs for analysis. If desired, texture can be analyzed in the two arcs parallel to traffic, and two arcs perpendicular to traffic, to investigate directional effects of texture (*33, 34*).

Henry et al. (*28*) found the CTM useful for calculating the International Friction Index (IFI) when used in conjunction with the DFT. The IFI is used in the European Union to harmonize friction measurements in the different countries. The IFI includes a friction number (FN60) that indicates

the friction at a slip speed of 60 km/h and a Speed Constant (Sp) that indicates the change in friction with speed. With these two values, it is possible to calculate the friction at any speed. Henry et al. used the DFT to determine FN60 and the CTM to determine Sp. Results correlated closely with other techniques to determine FN60 and Sp.
McGhee and Flintsch (*35*) compared the CTM to high-speed, dynamic texture measuring equipment. The high-speed systems included the ICC system manufactured by International Cybernetics Corporation and the MGPS system, which is a commercial version of the FHWA's road surface analyzer (ROSAN). The devices were used on 22 surfaces at NASA's Wallops Flight Facility and seven surfaces on Virginia's Smart Road.

McGhee and Flintsch found the results from the CTM and sand patch test to demonstrate "remarkable agreement." They also report that the CTM results were highly correlated to the two high-speed measuring systems. Analysis of the CTM data allows more detailed investigation of the texture to determine what is producing the texture and whether it is positive (raised), negative (grooved) or neutrally textured. The only limitation that they note with the CTM as opposed to the high-speed systems is that the stationary measurement does not allow evaluation of the fluctuation in macrotexture down the length of the pavement (*35*). For the purposes of this research, however, high-speed systems would not be appropriate for use in the lab.

<u>High Tech Approaches</u>
As a result of technological advances, there are other methods of determining texture in the laboratory and field. For example, research at Worchester Polytechnic Institute resulted in scanning laser position sensor (SLPS) for use in measuring runway surface texture and relating texture to tire wear in NASA sponsored research. Other devices use interferometry, structured light (lasers and strobes), stereo photography, fractal analysis and more (*36*). These approaches are quite sophisticated, still in the developmental stage and not readily available for use. Therefore, they are not considered further for use in this project.

<u>Summary and Discussion</u>. The literature review revealed a wide range of technologies for the evaluation of surface texture from simple, low-tech estimates to sophisticated, high tech measurements. The volumetric methods are quite simple, but are prone to significant variability, especially on highly textured surfaces. They are also generally recognized as "cumbersome" (*1*). The outflow meter also has problems on highly textured surfaces. All of these devices are limited in the sense that they give only a gross average of the texture over the tested area. No further analysis of the nature of that texture can be accomplished.

Stylus devices can give more information about the nature of the texture over a limited area, but have been superseded by technological advances.

Laser-based devices can give better resolution, larger coverage area, faster measurement and more analytical capabilities than the stylus devices. One, the CTM, is commercially available and ready for use. It appears to be the most promising device currently available.

Other high tech approaches may be developed further in the future, and may someday surpass the CTM, but they are not currently ready for widespread use.

User Experience

Based on the literature review, the DFT and CTM clearly appeared to be the most suitable candidates for use in this research. The data they produce has been used successfully and correlates with other, tried and true test methods (sand patch, outflow meter on non-porous surfaces, towed friction trailer, etc.). The techniques, however, provide more information than some of the older test methods. For example, the CTM can provide directional texture measurements and actual texture profiles, whereas the sand patch can only indicate the average texture over an area. Both the DFT and the CTM are suitable for laboratory and field use. They can also be used on pavements or mixture samples to measure both micro- and macrotexture effects.

To learn more about these devices, the researchers conferred with some users of the equipment. As noted in the literature review above, the Virginia Transportation Research Council researchers (McGhee and Flintsch) were very favorably impressed with the CTM.

Larry Scofield of the Arizona DOT has used the DFT and CTM for over two years. His testing has mainly been in the field. He reports good success with use of both devices. Although the software is not as user-friendly as it could possibly be, Scofield noted that the devices are rugged for field use. He has recommended the devices to a number of organizations.

NCAT has been most helpful. They have had the DFT and CTM for about one year. They developed a laboratory polishing device, as reported earlier, to polish slabs for testing. They have also used the devices on the NCAT track and various field projects where they have been measuring pavement noise. NCAT recommends both devices and is very satisfied with their utility.

In addition, NCAT brought the devices to Indiana when visiting for another research project in September 2003. NCAT demonstrated the use of both devices on three different pavement surfaces, including porous friction course, SMA and conventional hot mix asphalt. The principal investigator (PI) was able to observe the testing and was able to operate the equipment with a minimum of instruction. The software does involve a number of steps, but is not too difficult to learn. The tests themselves are quite rapid, and the data is impressive in its completeness and sensitivity. Overall, the PI was left with a very favorable impression of the equipment and its capabilities.

DFT and CTM Data Comparison

The data collected by NCAT in Indiana in September 2003 is summarized here to illustrate how the DFT and CTM data can be used and what it may reveal. This is preliminary data collected during a field comparison of a porous friction course (PFC), SMA and conventional HMA surface. The data are considered preliminary primarily because the PFC and SMA were tested before they were opened to traffic, which would wear away the initial asphalt film coating on the pavement surface. Friction data is generally not collected in Indiana until traffic has had a chance to remove this film coating and expose the aggregates at the surface, which are largely responsible for pavement friction over the service life of the pavement.

The PFC and SMA are located on I74 east of Post Road near Indianapolis. These surfaces are being studied under another SQDH project, *Field Evaluation of Porous Asphalt Pavement*. They were placed in August and September 2003. The conventional surface is located on US52 east of the Wabash River in Lafayette, Indiana, and was placed in June-July 2003. This section was immediately reopened to traffic, so the asphalt film had been removed prior to testing with the DFT and CTM. All three mixtures contain steel slag as a coarse aggregate. The conventional surface also has dolomite coarse aggregate in a 50-50 blend with the steel slag, as specified by the Indiana DOT Standard Specifications.

The DFT data are summarized in Table 1. This table shows the average friction reading from the DFT as a function of speed for all three mixes. The friction was measured at five locations for the PFC and SMA, but only at three locations for the conventional HMA due to traffic considerations. The standard deviation of the friction measurements is shown in parentheses in Table 1.

Table 1 Average DFT Numbers versus Speed and Pavement Type

Pavement Type	Average DFT Number (Standard Deviation)		
	20 kph (12 mph)	40 kph (24 mph)	60 kph (36 mph)
PFC	0.51 (0.03)	0.45 (0.03)	0.42 (0.03)
SMA	0.37 (0.01)	0.31 (0.01)	0.29 (0.01)
Conventional	0.52 (0.01)	0.47 (0.01)	0.44 (0.01)

This data shows that initially, the SMA has lower frictional resistance than the PFC or the conventional surfaces, which are fairly comparable. Since the SMA consists of a "bony" aggregate skeleton filled with a mastic of asphalt binder and fibers, the lower friction values are not unexpected when compared to mixtures with less binder and a more open texture. It is expected, however, that the friction of both the SMA and the PFC will increase when traffic wears away the asphalt coating and exposes the steel slag aggregate at the surface. The PFC would be expected to have a higher friction value due to its higher macrotexture unless or until the surface texture is lost or clogged with fines. The friction values do decrease as the speed increases, as expected. The rate of decrease appears to be fairly constant among the mixture types at this time.

The data also seems to show that the PFC is more variable than the other two surfaces, since it has a higher standard deviation. The variability is still quite low, however; this standard deviation yields a coefficient of variation of about 5%, which is quite good. Coefficients of variation as high as 15-20% are not uncommon for typical construction materials testing. Follow-up testing will be performed after traffic has had a chance to wear away the film coating to see if the PFC increases in friction and, possibly, decreases in variability.

The CTM data is summarized in Table 2. This data shows the average mean profile depth and standard deviation for each pavement type.

Table 2 Mean Profile Depth versus Pavement Type

Pavement Type	Mean Profile Depth (Standard Deviation)
PFC	1.37 (0.13)
SMA	1.17 (0.14)
Conventional	0.30 (0.05)

This data shows that the PFC and SMA both have significantly more texture depth than the conventional surface, with the PFC having the highest depth. The PFC and SMA also have more variability, as indicated by the higher standard deviations. This seems reasonable; the conventional surface has a more uniform gradation, which would produce a more uniform surface texture. The PFC and SMA have gap-graded aggregate structures, so there could be more variability from one location to another. The coefficients of variation are still less than 12%. For the SMA, some of the texture is reduced due to the presence of the mastic of asphalt binder and fibers. The texture readings on the PFC do not indicate that the surface is more variable than the SMA, although the friction measurements were somewhat more variable.

There are additional analyses that can be done on this data, such as looking at directional effects on the CTM data and determining the International Friction Index. Since the PFC and SMA have not yet been exposed to traffic, however, it is premature to place great significance on this data. Further testing and analysis will be performed in subsequent phases of this research program. At this time, the data does show that the DFT and CTM are able to differentiate between surface types. The data also appears meaningful since it follows expected trends (decreasing friction with increasing speed, differences between surface types, etc.). The level of variability is acceptable, although further analysis is needed to understand why the friction testing was more variable on the PFC than the other two surfaces.

Recommended Test Methods

Based on the literature review, user experience, limited data collection and the overall objectives of this research effort, then, the DFT and CTM appear to be very well suited to meeting the objectives of this research program. It is recommended that these devices be purchased using the RSPA funding provided through the Institute for Safe, Quiet and Durable Highways (SQDH). The equipment will have application for this research project as well as many future projects, field evaluations, etc., for all pavement surface types.

In addition, it is recommended that a polishing device similar to that developed by NCAT be used to accelerate the polishing of slabs for testing with the DFT and CTM. Since much of the development work has been done, the polishing device we fabricate can be somewhat simpler than that fabricated by NCAT, lowering the cost. For example, NCAT has determined that it is not necessary to vary the speed of rotation of the wheels on the slab during polishing. The NCSU polishing device and others also typically work at a fixed speed. Gearing to allow varying the speed of rotation, then, will not be required.

Lastly, for fabricating the slabs, we plan to try using a “rolling pin” approach to fabricate 508 × 508 × 38 mm (20 × 20 × 1.5 in) slabs for polishing and testing. The NCSC has used the rolling pin method to successfully fabricate specimens for noise testing on the Tire-Pavement Test Apparatus (TPTA) at SQDH. The TPTA specimens are curved arcs that fit around a 3.65 m (12 ft) diameter ring. By calculating the volume of the form and weighing the amount of mix to be placed in the form, the NCSC was able to control the density of the finished test section. The mix is rolled until its surface is flush with the form. The NCSC has two different rollers available for use. One roller is operated by hand by two to three people. The other can be mounted on a forklift and rolled across the surface, if additional force is needed to compact the mix. The slabs will be compacted into wooden forms of the proper dimensions to control the volume and to allow for handling the slabs after compaction and during testing.

Since this approach uses a rolling motion and the density of the specimen can be controlled, it is hoped that this will produce fairly realistic pavement surfaces for evaluation. This can be verified by measuring the resulting surface texture using the CTM and comparing it to existing pavements with similar aggregates and mix designs. (It is not possible to use the CTM on the TPTA specimens due to their curvature.)

If the rolling pin does not produce a reasonably realistic surface texture, the researchers will have to investigate other options. There is a linear compactor at Purdue that is similar to the compactor NCAT uses. It could be modified as NCAT did, but the costs would be much higher. In addition, since that compactor is currently used for compacting Purwheel test slabs, the use of the device would have to be coordinated with other research in progress on campus. Before going to this effort, it would be wise to first evaluate the surface texture produced at NCAT to see if it is any more realistic than the rolling pin.

Photographs of the recommended devices (DFT, CTM, NCAT's polishing device and the rolling pins) are shown in Appendix B.

Recommended Plan for Follow-Up Study (Phase II)

The following describes a preliminary plan for completing Phase II of this research program. Phase II includes field testing to establish a baseline of current friction levels and a statistically valid subset of a laboratory evaluation to investigate the effects of various percentages of high friction and common aggregates in different types of gradations. The goal of this phase is to begin to develop an understanding of the effects of changes in pavement macrotexture on friction and how these changes might offset the need for large amounts of high friction aggregate to provide at least the current friction levels. Phase II will also investigate whether the gradation changes required to change the macrotexture have an effect on other mix properties, including strength and cracking resistance.

Additional work may be needed to complete the test matrix, further refine the experimental design, or evaluate other mix properties, possibly including noise generation, in Phase III. At the conclusion of Phase II, an interim report will be prepared summarizing the findings of Phase II and considering the need for additional testing. The need for Phase III will be discussed with and determined by the Study Advisory Committee.

Experimental Design

The preliminary experimental design is shown in Table 3. This design is based on earlier discussions with the Study Advisory Committee. The design includes evaluation of the following factors:

- 3 Gradations – fine, coarse and S-shaped
- 2 nominal maximum aggregate sizes (NMAS) – 9.5 and 19 mm (3/8 and ¾ in)
- 2 high friction aggregates – slag from Indiana and quartzite from Iowa

- 3 common aggregates – dolomite from Indiana, hard limestone from Indiana and soft limestone from Iowa
- 3 friction aggregate contents – 10, 20, 40%

One fine aggregate and one binder will be used in all cells. Phase III could evaluate the effects of fine aggregate and binder grade at a later date.

The aggregates to test will be selected in consultation with the Study Advisory Committee. Both Iowa and Indiana lie in the Central Lowlands geomorphological region (Illinois Basin), so they do have some aggregate characteristics in common. Both have abundant carbonate aggregates, for example. However, the states have different practices and aggregate availability as well. Iowa has access to quartzite, which Indiana does not have. Indiana makes more use of blast furnace and steel slag than does Iowa. The limestones in Iowa tend to be rather soft, while harder limestones are available in Indiana. These similarities and differences were considered, and will be considered further, in selecting the aggregates to test.

The design above results in a total of 108 cells. Due to the time involved in fabricating and testing, as outlined below, it is not possible to complete testing of all cells within the time and budget of Phase II. The JTRP statistical consultant has advised on selecting a statistically valid subset of cells to test, as indicated by shading in Table 3. The states' interests, as voiced by the Study Advisory Committee, will factor in to selection of the cells for testing. For example, INDOT is particularly interested in the comparisons with slag and dolomite blends. They are not particularly interested in slag-limestone blends, so relatively few of these will be tested. The final selection of cells to test will be approved by the SAC. Depending on the Phase II results, the rest of the test matrix could be completed in Phase III, if desired.

A limited number of additional combinations of factors may be evaluated to investigate particular issues. For example, a high friction aggregate content of 30% may be tested in a few cells to correspond with current Iowa DOT practice. Some 12.5 mm mixes will be tested to correspond to typical INDOT practice. In addition, a few cells may be replicated with a different fine aggregate, to begin to investigate the effects of fine aggregate on pavement friction. Steel slag is being used more frequently in Indiana; some cells may be replicated with steel slag to compare to blast furnace slag. Lastly, current practice in Indiana frequently calls for 50-50 slag-dolomite blends; one or two of these will be tested to compare to the other slag content cells. If these investigations appear informative, Phase III could contain more detailed examinations of some or all of these factors.

Because of the number of factors being evaluated, there are many comparisons that can be drawn. The null hypothesis in each case will be that the friction levels are equal ($\mu_1 = \mu_2 = \mu_3 = \ldots$). The alternate hypothesis will be that the friction levels are not equal. It is anticipated that the null hypothesis will be rejected for many of the possible comparisons.

For example, for a given high friction aggregate, comparisons can be made between the different gradations. The null hypothesis would be that the friction levels provided by the fine, coarse and S-shaped gradations are equal ($\mu_F = \mu_C = \mu_S$). The alternate hypothesis is that the friction levels are not equal ($\mu_F \neq \mu_C \neq \mu_S$). Similar comparisons could be made between the different high friction aggregates, different friction aggregate contents, different nominal maximum aggregate sizes and different common aggregates.

Analysis of variance techniques will be used in the analysis to investigate the effects of interactions between the variables as well. The statistical analysis will be reviewed by the JTRP statistical consultant.

Testing Procedures

Six mix designs will be completed for the different gradations and nominal maximum aggregate sizes (3 gradations × 2 NMAS). To the extent possible, these will be based on examples of actual mixes from Indiana and Iowa. The same gradation and mix design will be used for all of the mixes for a specific gradation shape and nominal size. The aggregates will be sieved into individual size fractions and recombined to meet the same gradation. The binder contents will be adjusted to account for differences in absorption between the different aggregates.

All of the raw materials will be characterized. For the five aggregates being studied, the following characterization tests will be performed:

- Specific gravities (bulk and apparent) and absorption
- Angularity (fine and coarse)
- Sand equivalent value
- Flat and elongated content
- Gradation (though this will be manipulated to match mix designs)

The binder will be fully characterized according to AASHTO MP1.

Each individual mix will be tested to determine its maximum specific gravity. The bulk specific gravity and air voids will be determined for each gyratory specimen and will be estimated for each compacted slab based on weight of mix and volume of mold.

For each cell selected for testing in Phase II, the mixture will be produced in the laboratory and compacted into the wooden friction testing molds to about 6-7% air voids, to approximate field compaction. Due to the fairly large sample size and time for polishing, only one replicate friction slab is planned for each cell tested. Replicate friction and texture measurements can be made on each slab at various times during polishing. In addition, to evaluate the reproducibility of the polishing, replicate samples will be made and polished for at least six cells early in Phase II. If the polishing is not found to be reasonably reproducible, the experimental design for Phase II may need to be revised, in consultation with the SAC and statistical consultant, to allow for more replicates of fewer cells. Alternatively, additional replicates may be planned for Phase III.

To evaluate any possible detrimental effects of changes in the mixtures to increase macrotexture and friction, selected mixes will be tested for strength (complex shear modulus (G*) and dynamic modulus (|E*|) at high temperatures) and cracking resistance (indirect tensile testing). It is not feasible to perform these tests on every cell in the design due to budgetary considerations, so the specific cells to test will be determined based on preliminary friction testing or texture measurements. It is anticipated that about 20 to 24 cells will be tested, probably including high and low texture friction samples, as well as those that most closely correspond to current practice.

Work Time Schedule

The work outlined for Phase II is planned to take 15 months. A work time schedule is shown in Figure 1. This schedule is based on testing half of the complete experimental design shown in Table 3. Completion of the study according to this time frame will require collecting most, if not all, of the study materials before Winter 2003.

Work can begin as soon as materials are collected. In order to expedite this project, NCAT has agreed to lend the research team their DFT and CTM for up to six weeks to establish the baseline field friction measurements and begin laboratory testing. For example, the investigation of reproducibility of polishing could begin immediately. Because NCAT has many uses for their equipment, however, there will still be a need to purchase the equipment to complete the study. Past evaluations at Wallops Island have shown the CTM and DFT results to compare favorably from one device to another. Comparisons will be made between the NCAT devices and those purchased for this study to ensure the two devices are repeatable.

Because of the seasonal variations in field friction values, and because the lowest friction levels are of concern, determining the baseline friction values should be conducted in the Fall, as planned here. The NCAT devices will be available for loan in October and November 2003.

Sufficient funding is currently available from Indiana and Iowa to complete Phase II as outlined in this report. No funding currently exists for Phase III, however, Phase III is not expected to begin until January 2005, at the earliest. If the research team and SAC agree that Phase III is needed, additional funding will be sought from the two sponsoring states, additional states or alternative funding sources.

Conclusions and Recommendations

The literature review summarized here, supplemented by personal contacts with other researchers and observations of testing in progress, have lead to the following conclusions and recommendations.

- The literature strongly suggests that both microtexture and macrotexture are critically important factors determining the frictional resistance provided by a pavement surface, as posited in the original proposal
- The microtexture depends on the type of aggregate and determines the frictional resistance at low speeds.
- The macrotexture is dependent on the overall texture of the pavement and is influenced by the aggregate sizes and gradation, among other factors. Macrotexture affects the change in friction with increasing speed.
- Most commonly used tests for frictional resistance measure the microtexture or other property of the coarse aggregate alone and do not account for the effects of pavement macrotexture.
- After a thorough literature review, the Dynamic Friction Tester (DFT) appears to hold the most promise for meeting the objectives of Phase II of this research program. The DFT

is influenced by both micro- and macrotexture and can be used on pavement samples in the laboratory or the field.

- NCAT has developed an accelerated polishing device for use with the DFT in the laboratory; this device is recommended for use in Phase II.
- The literature review also pointed out the need to assess the pavement texture to quantify the effects of macrotexture. The Circular Track Meter (CMT) appears to be well suited to characterizing the surfaces to be studied under Phase II of this project.
- The DFT and CTM are companion devices that can be used together to determine the International Friction Index, which allows determination of the frictional resistance of a pavement at any speed and is influenced by both micro- and macrotexture.
- The DFT and CTM are highly recommended by several different users in the United States.
- A preliminary plan was developed for Phase II of this research program based on use of the DFT, CTM and NCAT polishing device. This plan is being presented to the Study Advisory Committee for review, possible refinement and approval.

Table 3 Preliminary Experimental Design

NMAS			9.5 mm (3/8 in)									19mm (1/2 in)								
Gradation			Coarse			Fine			S-shaped			Coarse			Fine			S-shaped		
Common Agg*			D	HL	SL	D	HL	SL	D	HL	SL	D	HL	SL	D	HL	SL	D	HL	SL
Friction Agg Type and Content, %	Slag	10																		
		20																		
		40																		
	Quart -zite	10																		
		20																		
		40																		

*D = Dolomite, HL = “Hard” Limestone, SL = “Soft” Limestone

Supplemental Experiments include examination of:

- Repeatability of polishing
- Quartzite at 30% addition rate
- 50-50 slag dolomite blends

These would involve limited testing of additional analysis cells.

Other possible supplemental test cells include:

- Steel slag vs. blast furnace slag
- Different fine aggregate (slag vs. natural)
- Different binder grade

Selection of supplemental test cells depends on time, funding availability and interests of the Study Advisory Committee.

Figure 1 Phase II Work Time Schedule

Year	2003			2004											
Task	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
3. Finalize Experimental Design															
4. Establish Baseline												*	*		
5. Laboratory Testing															
6. Phase II Report															

*Additional field testing, if required.

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APPENDIX A – Comparison of Test Methods

Devices for the Accelerated Polishing of Aggregates and Mixes					
Device	**About Device**	**Properties**	**Strengths**	**Weaknesses**	**Specs/Used By**
British Polishing Wheel	Wheel for polishing away macrotexture	Curved aggregates specimens polished by a rotating wheel.	Accelerated polishing for lab testing. Bench sized.	Coarse aggregate coupons only. Does not affect macrotexture or mix properties	ASTM D 3319
Michigan Indoor Wear Track	Large circular track	Wheels centered around pivot point, move in circle around track	Close to real world.	Track is very large and cumbersome. Time consuming sample preparation. Used for aggregate only.	MDOT
NCSU Polishing Machine	4 wheels rotate around central pivot	Four pneumatic tires are adjusted for camber and toe-out to provide scrubbing action for polishing	No need for water or grinding compounds, can polish aggregate or mixes	Polishes a relatively small area or few number of samples	ASTM E 660
NCAT Polishing Machine	3 wheels rotate around central pivot	Three pneumatic tires are adjusted for camber and toe-out to provide scrubbing action for polishing	Sized to match DFT and CTM.	New device developed by NCAT based on older devices.	NCAT
Penn State Reciprocating Polishing Machine	Reciprocating pad	Reciprocates rubber pad under pressure against specimen surface while slurry of water and abrasive is fed to surface.	Portable. Can be used to polish aggregate or mix in lab or field.	Polishes a relatively small area. Oscillation obliterates directional polishing. Fallen into disuse.	ASTM E 1393

Devices for the Testing and Evaluation of the Surface Friction of Aggregates and Mixes					
Device	**About Device**	**Properties**	**Strengths**	**Weaknesses**	**Specs/Used By**
British Pendulum Tester	Pendulum arm	Evaluates the amount of Kinetic Energy lost when a rubber slider attached to the pendulum arm is propelled over the test surface	Portable. Very simple. Widely used.	Variable quality of results. Cumbersome and sometimes ineffective calibration. Pendulum only allows for a small area to be tested.	ASTM E 303
Michigan Laboratory Friction Tester	Rotating Wheel	One wheel is brought to a speed of 40 mph and dropped onto the surface of the sample. Torque measurement is recorded before wheel stops	Good measure of the tire/surface interaction. Similar to towed friction trailer.	Poor measurement of pavement macrotexture. History of use on aggregate only.	MDOT
Dynamic Friction Tester	CTM	Measures the coefficient of friction	Laboratory or field measurements of microtexture	N/A	ASTM E 1911
North Carolina Variable Speed Friction Tester	Pendulum Type Testing Device	Pendulum with locked wheel smooth rubber tire at its lower end	Can simulate different vehicle speeds	Uneven pavement surfaces in the field may provide inaccurate results	ASTM E 707
PTI Friction Tester	Rubber slider	Rubber slider is propelled linearly along surface by falling weight	Tests in linear direction	Companion to Penn State Reciprocating Polisher. Fallen into disuse.	Formerly by PTI

Devices for the Evaluation of the Surface Texture of Mixes					
Device	**About Device**	**Properties**	**Strengths**	**Weaknesses**	**Specs/Used By**
Sand Patch	Sand spread over circular area to fill surface voids	Measures mean texture depth over covered area	Simple	Cumbersome. Poor repeatability. Average depth only.	ASTM E965
Grease Patch	Grease spread over surface	Measures mean texture depth over covered area	Simple	Cumbersome. Poor repeatability. Average depth only. Not widely used.	NASA
Silicone Putty Method	Silicone putty pressed onto surface	Measures mean texture depth over covered area	Simple	Cumbersome. Poor repeatability. Average depth only. Not widely used.	Texas Transportation Institute
Outflow Meter	Water flows from cylinder through surface voids	Estimates average texture	Simple. Quick.	For non-porous surfaces only.	FHWA
Dromometer	Stylus traces surface	Lowers a tracing pin, that creates a profile of the specimen surface	Can measure both micro and macro texture	Can only be used on small areas of pavement	Augustin, H. (Ref. 12)
Surtronix 3+ Profilometer	Stylus traces profiles	Horiz Res = 1 micrometer Vert Res = 0.001 micrometer Traverse Length = 25.4 mm	Can read micro and macrotexture	Can only be used on small areas of pavement	Gunaratne, M. (Ref. 13)
Circular Texture Meter	Laser based	Laser mounted on an arm that rotates on a circumference of 142 mm and measures the texture	Used with DFT can calculate IFI. Fast. Portable. Repeatable.	Measures small area. Relatively new.	ASTM E 2157

APPENDIX B

Photographs of Recommended Test Equipment

Figure B1 NCAT Slab Polisher

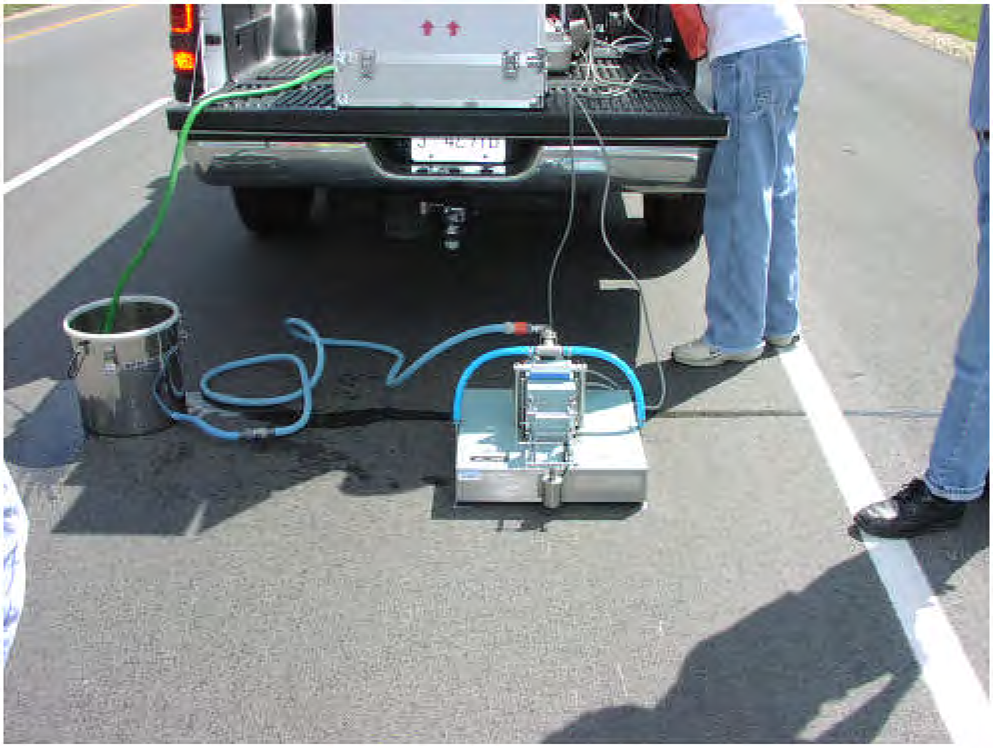

Figure B2 Preparing the DFT for Friction Testing

Figure B3 Measuring texture with Circular Track Meter

Figure B4 Compacting noise testing slabs with manual rolling pin

Figure B5 Forklift mounted rolling pin for greater force