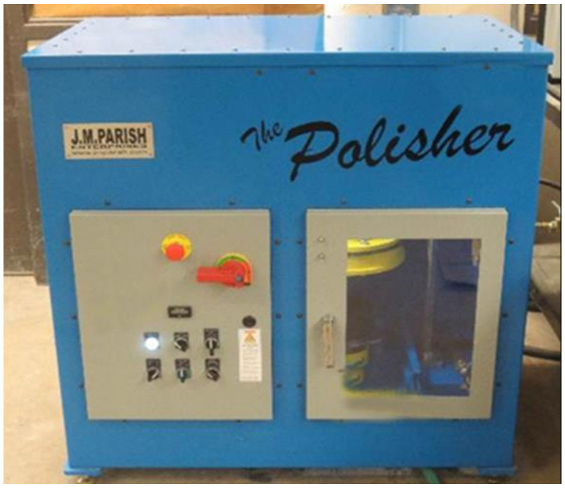
Long Term Validation of an Accelerated Polishing Test Procedure for HMA Pavements



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Prepared for:
The Ohio Department of Transportation,
Office of Statewide Planning & Research

State Job Number 134413

April 2013

Final Report

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
FHWA/OH-2013/3			
4. Title and Subtitle		5. Report Date	
Long Term Validation of an Accelerated Polishing Test Procedure for HMA Pavements		**April 2013**	
		6. Performing Organization Code	
7. Author(s)		8. Performing Organization Report No.	
Dr. Robert Y. Liang		**N/A**	
9. Performing Organization Name and Address		10. Work Unit No. (TRAIS)	
University of Akron Department of Civil Engineering Akron, OH, 44325		11. Contract or Grant No.	
		SJN 134413	
12. Sponsoring Agency Name and Address		13. Type of Report and Period Covered	
Ohio Department of Transportation 1980 West Broad Street Columbus, Ohio 43223		**Final Report**	
		14. Sponsoring Agency Code	
15. Supplementary Notes			
16. Abstract			

The Ohio Department of Transportation (ODOT) has set strategic goals to improve driving safety by maintaining smooth pavement surfaces with high skid resistance. ODOT has taken the initiative to monitor pavement friction on Ohio roadways and remedy the pavement sections with low skid resistance. However, this is a passive and reactive approach toward the problem. A more proactive approach would be to test hot mix asphalt (HMA) in the laboratory during the mix design stage to ensure that the aggregates used will provide adequate friction over the life of the pavement. With the validity of a research-grade polishing machine established in a previous study, ODOT has initiated this project to conduct a long-term field study to collect field performance data over a longer time period. The research effort was aimed at further validating the applicability of the previously developed laboratory test protocol and acceptance criteria through a correlation and comparison study with long-term field performance data. This research has produced the following deliverables: (a) a new commercial grade accelerated polishing machine called "The Polisher," (b) models for predicting the field performance of asphalt pavement friction under traffic, and (c) supplemental notes with draft specifications for polishing HMA samples and for testing friction properties. The commercial grade polishing machine and the supplemental notes were recommended for ODOT implementation.

17. Keywords		18. Distribution Statement	
Accelerated Polishing, Friction, HMA.		**No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161**	
19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	**Unclassified**	**269**	

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Robert Y. Liang

April 2013

Prepared in cooperation with the Ohio Department of Transportation
and the U.S. Department of Transportation, Federal Highway Administration

Table of Contents

List of Tables

List of Figures

1. INTRODUCTION

1.1. Statement of Problem

Highway accidents are a leading cause of death and injury around the world. Between 1990 and 2000, an average of 6.4 million highway crashes occurred annually nationwide (NHTSA 2004). In 2011, 32,310 people died in motor vehicle crashes, down 1.7 percent from 32,885 in 2010, according to the U.S. Department of Transportation's National Center for Statistics and Analysis of the National Highway Traffic Safety Administration. The frictional properties of pavement surfaces play an important role in highway safety (Henry 2000). Pavement surfaces must maintain an adequate level of friction at the tire pavement interface in order to provide a safe surface for traveling vehicles. The abrasion that occurs in asphalt concrete pavement due to traveling vehicle over time can polish the surface of the hot mix asphalt (HMA) and reduce friction, thus creating a serious safety concern, particularly under wet conditions.

The Federal Highway Administration (FHWA) has issued a Wet Skid Accident Reduction Program to encourage each state highway agency to minimize wet weather skidding accidents by identifying and improving the sections of roadways with high occurrence of skid accidents and by developing new surfaces at these sections to provide adequate and long-lasting skid resistance properties.

The Ohio Department of Transportation (ODOT) has set strategic goals to improve driving safety by maintaining smooth pavement surfaces with high skid resistance. ODOT has taken initiative to measure and monitor the skid number (SN; a number representing the friction properties measured by a locked wheel skid trailer) for pavement sections in areas where a high rate of wet weather related accidents occur. Once the measured SN falls below a certain threshold value, ODOT resurfaces the pavement to maintain high skid resistance and ensure driving safety. The practice of monitoring and remedying the pavement sections with low skid resistance is important; however, it is a passive and reactive approach toward the problem. A more proactive approach would be to test the HMA in the laboratory during the mix design stage to ensure that aggregates used in the HMA will provide adequate friction as expected over the life of the pavement. Ensuring the use of appropriate aggregate to provide friction over the pavement life expectancy is a desirable goal.

Skid resistance is known to be affected by such factors as bleeding of asphalt, polished aggregate, smoothened macrostructure, rutting, and inadequate cross slope. However, aggregate and mixture characteristics remain the most dominant controlling factors. The ability of different aggregates to resist polish and wear is related to mineralogical and chemical compositions as well as physical properties, such as texture, particle size, shape, and gradation. Previous studies commissioned by ODOT to study the polishing and friction characteristics of Ohio aggregate sources include Colony (1984 and 1992), Liang and Chyi (2000), Liang (2003), and Liang

(2009). Colony's research indicated that traffic conditions, properties of construction material, and geological features were strong contributors to variations of skid number (SN) throughout the state highways. Furthermore, Colony pointed out that the properties of different aggregate sources and mix design have important bearings on the measured variations in SN over time in different pavements. While Liang (2003) dealt specifically with blending of aggregates, Liang and Chyi (2000) has developed a complex, time consuming, and labor-intensive test procedure for identifying potential aggregate sources that may present rapid polishing and low residual friction properties. The test procedure involved the use of British pendulum tester (BPT; ASTM E303-93) to determine the friction properties and the British Wheel (ASTM D-3319) for accelerated polishing of aggregates. Mineralogical analysis using thin sections and acid insoluble residue (AIR) test were included in the test protocols of Liang and Chyi (2000) to identify the minerals that dominate the polishing properties of aggregates. It is noted that the test procedure developed by Liang and Chyi (2000) only deals with the polishing and friction properties of aggregate, not the performance of the HMA. There is a need to develop a new accelerated polishing equipment and friction measurement device to reliably indicate the polishing and skid performance of aggregates in the asphalt pavement at the stage of mix design.

Liang (2009) developed a laboratory scale accelerated HMA polishing machine. This research grade accelerated polishing machine was designed and fabricated with several practical considerations in mind. These considerations include: (i) versatility of testing different HMA specimens prepared with the conventional compaction methods (i.e., gyratory compaction or roller compaction), (ii) the specimens could be prepared as part of mix design procedure (i.e., using the gyratory compactor together with the industry standard 6-inch-diameter mold), (iii) test duration should be relatively short, (iv) test procedure including test specimen preparation and friction measurement techniques should be relatively simple and repetitive, (v) test procedure should require minimum labor efforts, and (vi) test results should provide realistic indication (screening outcome) of the polishing and friction behavior of the HMA specimens. Liang (2009) demonstrated the capability of the research grade polishing machine through a series of validation tests, including repeatability, comparisons with British Wheel Test results of aggregate samples, and image analysis of exposure area of aggregate during polishing test. A tentative test procedure with the accompanied acceptance criteria were also recommended in the report. Nevertheless, very limited resources were spent on collecting field performance data for comparison with laboratory obtained polishing data using the developed accelerated polishing machine.

With the validity of the research grade polishing machine established and the initial limited performance data collected with fairly positive comparison results with lab test data, ODOT has decided to conduct a long-term field study to collect field performance data over a longer time period. To this end, this research was initiated to focus on long-term validation of an accelerated polishing test procedure for HMA pavements. However, since polish rates are non-linear and mix gradation and aggregate source are varied, it was recognized that statistical means need to be utilized in developing any predictive model for friction degradation with traffic for any given material properties measured by the accelerated polishing machine.

1.2. Objective of Study

The main objective of this research is to validate the applicability of the previously developed laboratory test protocol and acceptance criteria associated with the previous research (Liang 2009) through a correlation and comparison study with field long-term performance data. In addition, a production grade polishing machine based on the design guidelines of the research grade polishing machine outlined in Liang (2009) will be developed and delivered to ODOT lab for routine use. The specific objectives can be enumerated as follows:

- Continue to improve and refine the laboratory test protocols to ensure ease of implementation by potential users such as contractors, aggregate producers, and DOT material engineers;

- Validate the acceptance criteria by relating lab measured time-dependent friction loss behavior to the time history of field performance data using the selected pavement test sections throughout Ohio;

- Develop ODOT Supplemental Specifications incorporating the developed equipment and test procedures for friction/polishing criteria during the mix design of the hot mix asphalt for a surface course.

1.3. Scope of the Work

This research involved laboratory work, field measurement work, and model development. In addition, a production-grade polishing machine was developed and delivered to ODOT Lab. Supplemental specifications were developed for ODOT implementation. The specific works performed under each category are presented below.

1.3.1. Laboratory Work

The laboratory work encompasses the following main tasks:

1. Refine the polishing machine to improve its operation efficiency. Areas for improvement include the following considerations: (1) on the fly friction measurement capability, (ii) automatic water feeding device, (iii) dedicated and standard specimen size, and (iv) small horsepower motor, and (v) robust equipment control module. The outcome of this task was an industry grade accelerated polishing machine ready for large quantity production.

2. Develop a streamlined laboratory test procedure. Previous research work was performed as a pure research activity; therefore, it is necessary to eliminate unnecessary steps in order to

streamline the test procedure. The outcome of this task was the development of a test procedure and a user manual in association with the industry grade polishing machine. In addition, the sample preparation methods, minimum number of replicate specimens, and data reporting format were recommended.

3. Establish the necessary quality assurance and quality control (QA/QC) process for the laboratory testing procedure. The outcome was incorporated into the test procedure. Minimum requirements for test accuracy, reliability, and repeatability were also established.

4. Establish the operating parameters (e.g., vertical load, rotational speed, water feeding rate, test duration, etc.) of the polishing machine to ensure that optimum results are obtained. The outcome of the laboratory research was used to develop the industry grade production-level polishing machine.

1.3.2. Field Work

The main purpose of the field work was to conduct tests on the selected eight pavement test sections at least once a year for three years so that the long-term data could be obtained for prediction model development. Specific tasks carried out at each of the test pavement section were as follows.

1. Coordinate with ODOT engineers to obtain SN of the pavement sections on a yearly basis.

2. Arrange traffic control support from ODOT to enable the University of Akron (UA) research team to conduct field measurements at the selected pavement sections. Various types of tests conducted at each location include friction measurement using the dynamic friction tester, texture measurement using the circular texture meter, friction measurement using the British pendulum tester, and rut depth measurement.

3. Obtain traffic data for each test pavement section.

4. Compile field data, including both ODOT and UA data, for subsequent data analysis and model development.

1.3.3. Correlation Study

The purpose of a correlation study is to establish predictive models for friction loss as a function of surface course material properties, traffic, and other influencing factors. It was intended to build a relationship between laboratory obtained friction and polishing data and those obtained from field testing of pavement sections. Specifically, there are two categories of correlations to be established: one is related to friction measurement (e.g., SN, friction number obtained from a dynamic friction tester, and British Pendulum friction number), and the second one is related to the rate of polishing, particularly concerning the laboratory test duration under accelerated polishing and the field skid number degradation curve for the pavement under the actual traffic and environmental conditions.

The development of the time scale difference between the laboratory test results and field performance data is challenging, since the traffic count and weather environment at each site can exert a significant influence on the rate of friction loss. To isolate multiple effects on the field measured performance data, some simple techniques such as examining the rate of friction loss, the total percentage drop of friction, and the normalized friction behavior have been analyzed in light of actual traffic history and weather conditions.

1.3.4. Supplemental Specifications

The research team developed for ODOT a draft of Supplemental notes on the use of the accelerated polishing machine, together with the friction measurement procedure and acceptance criteria. This guidance will ensure that any HMA produced will not only meet specifications but will also comply with friction/polishing requirements. The Supplemental notes were written in accordance with ODOT requirements. Final acceptance and adoption by ODOT requires approval by ODOT engineers.

1.4. Report Outline

Chapter II provides a brief summary of review of friction mechanisms of asphalt pavement and recent efforts to develop prediction models for friction degradation under in-service pavement conditions.

Chapter III presents the development efforts of a commercial grade, accelerated polishing machine for gyratory compacted samples. The original research grade polishing machine is described first with the design details and validations of the capabilities of the optimum operation parameters. The design guidelines and functionalities of a new polishing machine, referred to simply as “The Polisher”, are presented. Finally, the validation of the new polisher is provided at the end of chapter.

Chapter IV provides the results of a three-year effort in measuring friction and texture properties of six pavement sections in Ohio. A complete set of field measured data – including the SN, data obtained from the dynamic friction tester (DFT), and the mean texture depth (MTD) – is provided in Appendix D, while the condensed measurement data is presented in this chapter. Observations of the trend of friction degradation with time are noted. The field friction degradation data were used to develop prediction models and for validations.

Chapter V provides the details of the development of predictive models for SN(64)R (the skid number at a test specification of 64 km/hour using a ribbed test tire) and F(60) (the frictional resistance value generated at a slip speed of 60 km/hour) with in-service years. The models were tested successfully using field data. This chapter also discusses the Supplemental notes that were developed in this study (and are provided in Appendix E) to facilitate implementation of a procedure to evaluate suitability of aggregate sources and mix designs to provide adequate friction over the design life of a pavement.

Chapter VI provides a summary of work performed and conclusions based on the findings of this study. In addition, recommendations for implementation and future research are provided at the end of the chapter.

2. LITERATURE REVIEW

2.1. Background and Significance of Work

Maintaining adequate friction and texture properties of the pavement surface to ensure the safety of traveling vehicles has been an important mission of highway agencies. A common practice adopted by most highway agencies has been to regularly monitor friction by way of routine measurement of SN using a locked wheel skid trailer. Once the measured SN falls below the acceptable threshold value, maintenance work (such as resurfacing) would be carried out to remedy the situation. While this practice is commendable, it is a passive and reactive approach to the problem. A more rational approach would be to evaluate the mix design and aggregate sources during the material selection stage to ensure that friction properties of the construction material can be adequate for the intended design life of pavement. To achieve this, a validated laboratory test procedure utilizing an accelerated polishing machine is needed. At the moment, there is no standardized test procedure that can fulfill this need. The goal of this research is to develop such a test procedure, together with the delivery of an accelerated polishing machine and the corresponding acceptance criteria.

2.1.1. Mechanism of Polishing, Wearing and Skid Resistance

The skid resistance of a pavement is dictated by its surface texture, which can be divided into two scales: macrotexture (which has asperities larger than 0.5 mm) and microtexture (which has asperities smaller than 0.5 mm). The term *wearing* describes a process where the road surfaces will lose macrotexture or surface irregularities, while the term *polishing* describes the loss of microtexture from the road surface. Most researchers agree that the principal mechanism of polishing is the abrasion of the small aggregate asperities resulted from the rubbing action under loaded tires with the fine road detritus as the abrasive agent. The principal mechanism of wearing involves continuous abrasion resulting from loads and environmental changes such as freezing/thawing, wetting/drying, and oxidation. Polishing and wearing generally involve similar processes that vary only in the degree and the rate of material loss.

Friction, which is the force that resists the relative motion between two bodies in contact, is an essential part of the tire-pavement interaction. Not only does friction allow a driver to accelerate and maneuver a vehicle, but also it exerts a major determining factor in stopping a vehicle. The factors influencing the development of friction between rubber tires and a pavement surface include the texture of the pavement surface, the vehicle speed, and the presence of water. However, pavement skid resistance (or pavement friction) is defined as the ability of a travelled surface to prevent the loss of traction with the vehicle rubber tires.

Skid resistance and texture of pavement surface are two important parameters often measured during the service life of the pavement to ensure that the pavement meets the minimum required criteria for safety. Theoretically, the friction that develops between a rubber tire and a travelled pavement surface consists of two components: adhesion and hysteresis (Kummer 1966). As depicted in Figure 2–1, adhesion is the shear force between the tire and the pavement surface generated when the tire rubber slides over the aggregate surface asperities due to microtexture and the aggregate particles indent onto the rubber. In essence, adhesion can be viewed as the molecular bonds generated when the tire rubber deforms under load. The second friction component, hysteresis, is developed when the tire rubber deforms due to macrotexture (or irregularities) of the pavement surface. In essence, it can be viewed as the energy loss that occurs as the rubber is alternately compressed and expanded as it slides over the irregular pavement surface texture.

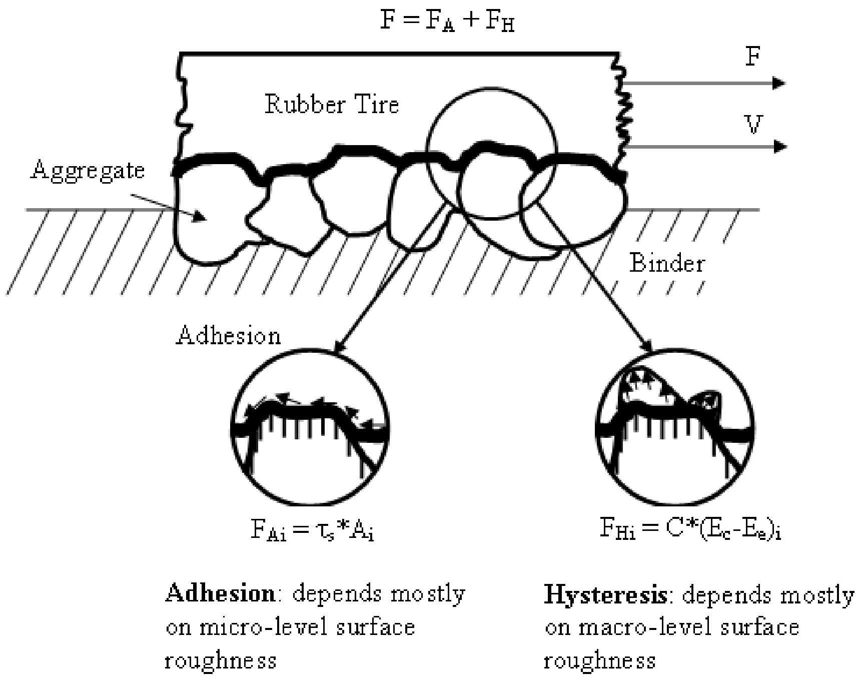


Figure 2–1: Schematic of adhesion and hysteresis of rubber-tire friction.

Figure 2–2 presents a schematic diagram of the contribution of adhesion and hysteresis to the friction factor. At low speed, friction is due mainly to adhesion. On the other hand, at high speed, the contribution of hysteresis becomes more significant. A pavement that is covered with a thin film of lubricant would provide only hysteresis.

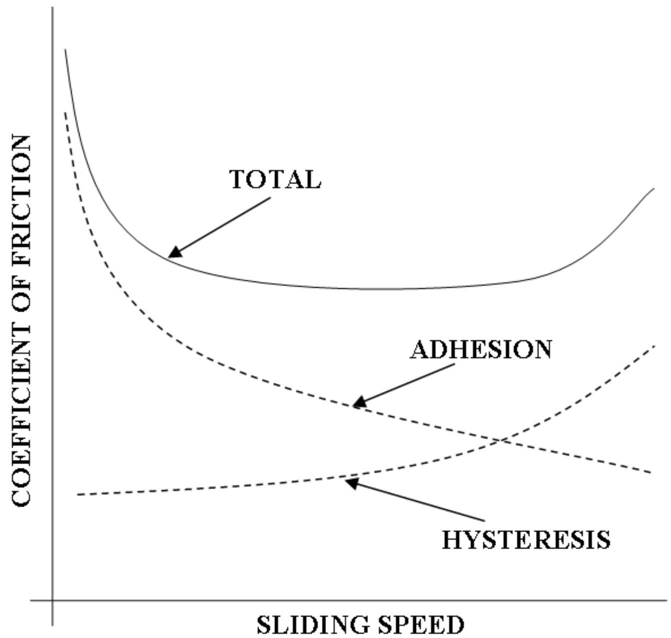


Figure 2–2: The contribution of adhesion (microtexture) and hysteresis (macrotexture) to the friction factor as a function of sliding speed (reproduced from Federal Aviation Administration 1971).

2.1.2. Factors Affecting Skid Resistance

The fiction between a rubber tire and the pavement surface is dependent on the two materials in contact, namely the type of rubber used and the materials that comprise the surface of the pavement. The type of rubber used is important because damping characteristics change with the type of rubber and its chemical composition. The pavement surface, as determined by the surface texture and viscoelasticity of asphalt materials, is also important in determining the magnitude of both adhesion and hysteresis.

The adhesion component is dependent upon the following factors:

1. Interface lubrication: dry surfaces provide higher adhesion than wet surfaces. The presence of lubricants tends to decrease the shear strength of the interface.

2. Sliding speed of rubber: adhesion increases with speed and reaches a maximum at a "critical speed." The critical speed ranges from 0.1 to 10 mph depending on the rubber type and temperature. For speeds above this "critical speed," adhesion decreases.

3. Pressure: adhesion also decreases as the loading pressure increases. Higher loading pressure is associated with an increase in the actual contact area; but that increase is not proportional to the increase in the loading pressure.

4. Temperature: the adhesion at a particular speed may increase, decrease, or remain unaffected by temperature changes at the interface due to the viscoelastic nature of the rubber and asphalt pavements.

On the other hand, the hysteresis component (Bazlamit 1993) is dependent upon the following factors:

1. Hysteresis will increase with increase in the damping ability of rubber.

2. Unlike adhesion, hysteresis decreases as the temperature of the interface increases.

3. Hysteresis is virtually independent of the loading pressure and lubrication.

2.1.3. Roughness and Texture

Pavement texture is the feature of the road surface that ultimately determines most tire-pavement interactions, including wet friction, noise, splash and spray, rolling resistance, and tire wear (NCHRP Synthesis 291, 2000). Pavement texture has been categorized into four ranges based on the wavelength of its components: microtexture, macrotexture, megatexture (wave-shaped road surface characteristics ranging from wavelengths of 50 mm up to 500 mm), and roughness or evenness. At the 18th World Road Congress, the Committee on Surface Characteristics of the World Road Association (PIARC) proposed the definitions of the wavelength range for each of the categories as shown in Figure 2–3 (PIARC 1987). The committee further proposed the range of the texture wavelengths that are important for various tire-pavement interactions, which are also shown in Figure 2–3. Wet pavement friction is primarily affected by the range described by microtexture and macrotexture, as can be seen in a vast number of recent studies, for example, by Davis (2001), Do and Marsac (2002), McDaniel and Coree (2003), Luo (2003), Flintsch et al. (2003), Hanson and Prowell (2004), Kuttesch (2004), Wilson and Dunn (2005), and Goodman et al. (2006). Because the range of microtexture and macrotexture will affect noise, splash/ spray, and tire wear, pavements designed with high friction values may have adverse effects on these characteristics.

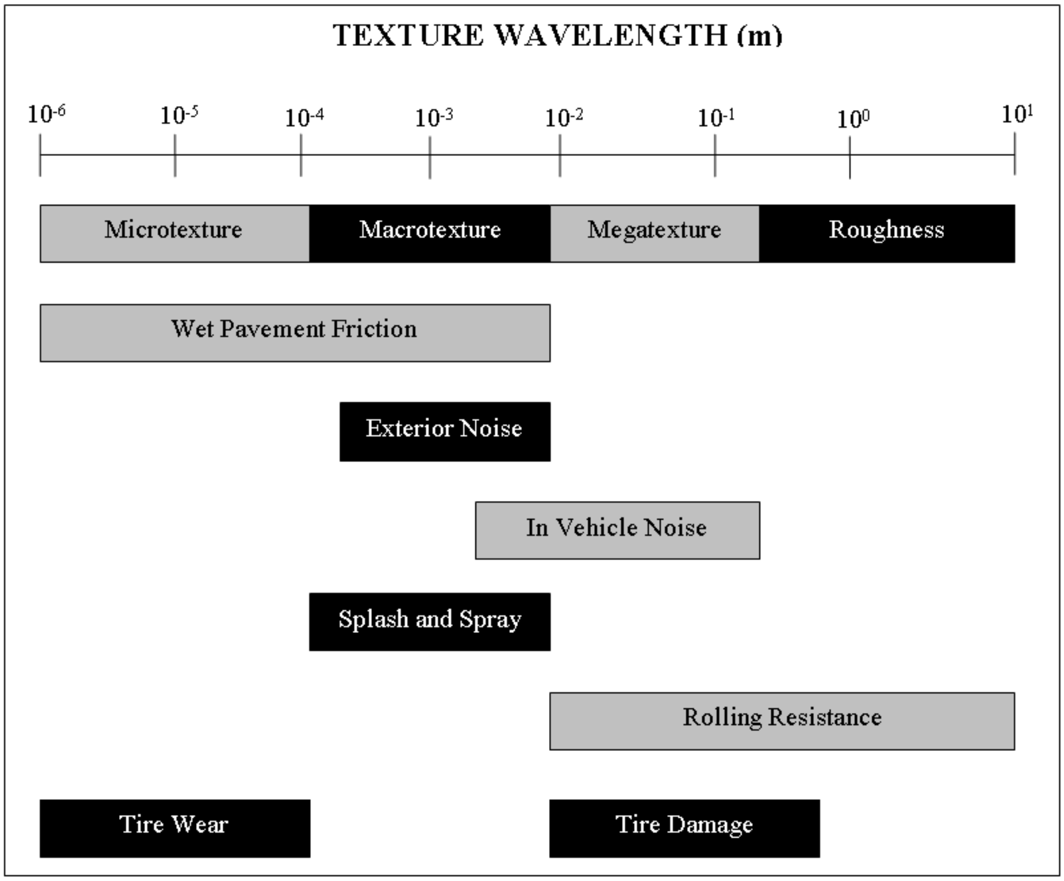


Figure 2–3: Texture wavelength influence on surface characteristics (reproduced from PIARC 1987).

A detailed description of microtexture and macrotexture is presented herein. Tiny grains of fine aggregate and features that make up the surface of coarse aggregate provide what is known as the pavement microtexture. Thus, microtexture is a function of aggregate gradation. In functional terms, microtexture is the most significant contributor to low speed skid resistance and provides a gritty surface to penetrate thin water films and produce good frictional resistance between the tire and the pavement. Microtexture describes wavelength that ranges from 0.1 mm to 0.5 mm and it is correlated to low speed friction. Features of the pavement surface that range from approximately 0.5 mm to 50 mm in length are classified as macrotexture. Macrotexture was shown to be the primary determining factor of high speed wet skid resistance (Flintsch and McGhee 2003; Chelliah et al. 2003; Henry, 2000; Janoo and Korhonen 1999; Dewey et al. 2001; Abe et al. 2002). Macrotexture is a result of the large aggregate particles in the mixture, and it is a function of aggregate type. Macrotexture provides drainage channels for water expulsion between the tire and the pavement, which allows better frictional resistance and prevents hydroplaning. Macrotexture can be estimated using volumetric or laser-based methods. Both the microtexture and macrotexture of asphalt concrete pavements are influenced by the properties of the coarse aggregates exposed at the wear surface, since the coarse aggregate in bituminous mixtures is more influential than other mix constituents in determining skid resistance (Dewey et al. 2001; Crouch et al. 1996). A schematic illustration of microtexture and macrotexture is shown in Figure 2–4.

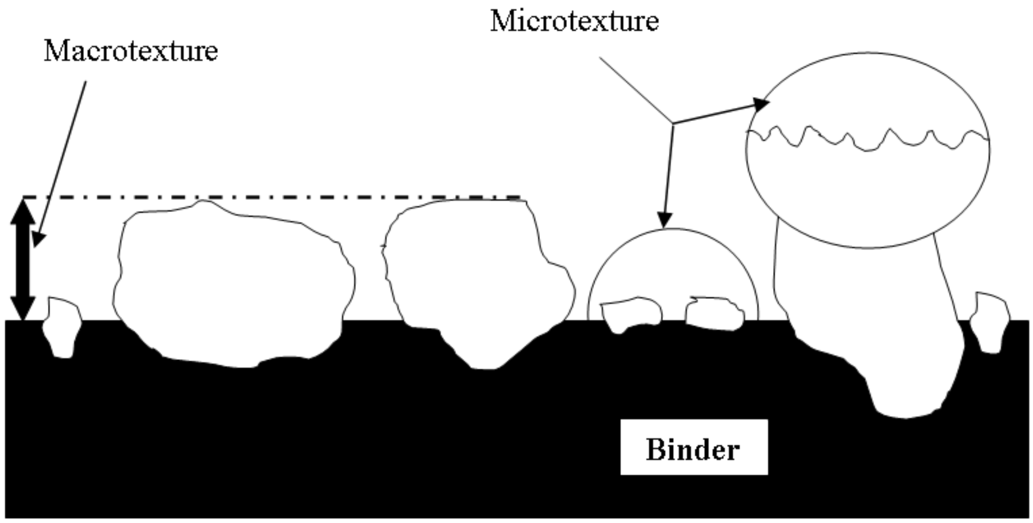


Figure 2–4: Schematic representation of microtexture and macrotexture.

Figure 2–5, on the other hand, presents the effect of microtexture and macrotexture properties on skid resistance as a function of speed (Janoo and Korhonen 1999). Clearly, to maintain a constant high skid resistance value at various speed levels, the pavement surface should have both good microtexture and macrotexture (Janoo and Korhonen 1999; NCHRP Synthesis 291, 2000). The change in the texture depends on the aggregate resistance to fragmentation, wear, and polishing. Aggregate fragmentation and wear depend on the toughness and hardness of the aggregate minerals and the aggregate itself. Polishing depends on the difference in hardness of the different minerals present in the aggregate (Janoo and Korhonen 1999). Surface texture can be defined in terms of microtexture and macrotexture; the terms used to describe the texture of a road surface are shown in Figure 2–6.

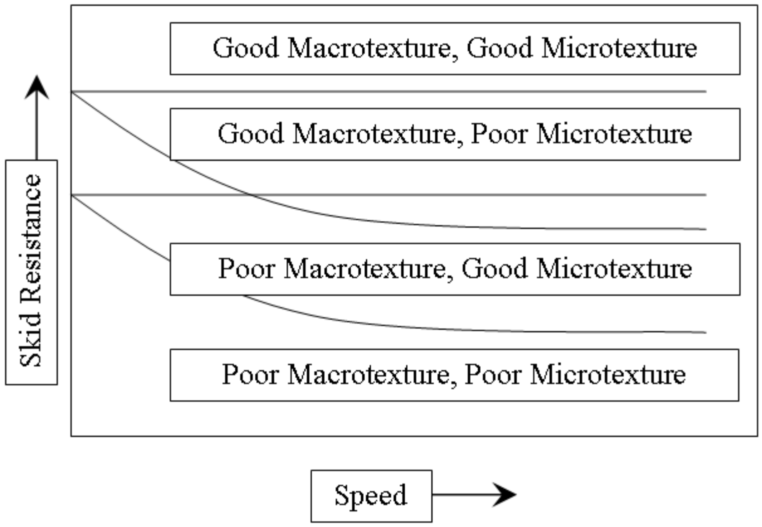


Figure 2–5: Effect of microtexture and macrotexture on skid resistance as a function of speed.

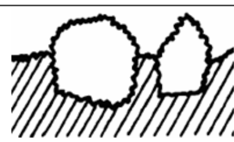
Surface		**Scale of Texture**	
		Macrotexture (Large)	**Microtexture (Small)**
A		Rough	Harsh
B		Rough	Polished
C		Smooth	Harsh
D		Smooth	Polished

Figure 2–6: Terms used to describe the texture of a road surface.

2.1.4. Importance of Aggregate Characteristics to Surface Performance

Aggregates constitute more than 90% by weight of asphalt pavement materials as shown in Figure 2–7. Strength and durability of aggregates often hold the primary concern of the designer, especially in bituminous pavement construction (Smith and Fager 1991; Kandhal and Parker 1998). Consequently, aggregate has a very significant role in surface performance. The role of aggregate is to provide a macrotexture that will induce tire hysteresis and facilitate water drainage in the tire-pavement contact area. Aggregate also provides a microtexture that will maintain a level of friction.

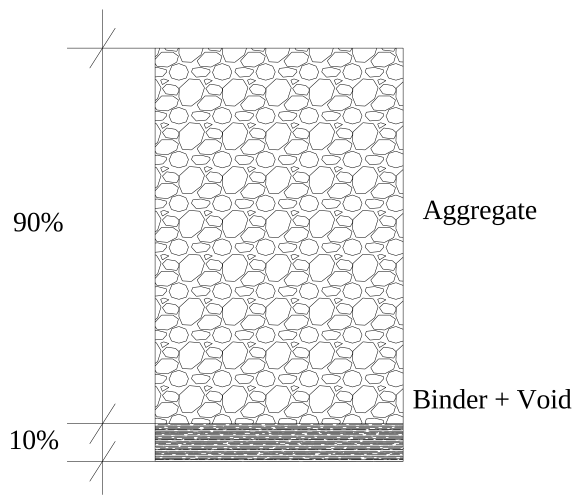


Figure 2–7: Weight phase diagram of hot mix asphalt.

Within the service life of an asphalt pavement, surface aggregates are subjected to various types of stresses. These stresses may induce differential wear that may be beneficial in restoring surface friction, or they may have detrimental effects such as cracking or scaling. In order for the aggregates to withstand wear that causes differential changes in surface macrotexture, the aggregate must be hard, tough, and possess well-bonded grains so that it will not be easily crushed or fractured under traffic loading stresses. The aggregate must also be chemically stable. If the aggregate resists excessive wear but undergoes slow differential wear, the macrotexture will be preserved and the microtexture will be improved.

According to Gandhi et al. (1991), among the aggregate properties that can affect friction, polish values and acid solubility (carbonate content) were found to be statistically significant. However, the carbonate content gave a better correlation than polish values. Also, when texture depth was included as an additional variable in the models with either solubility or polish values, the correlation coefficients increased slightly. American Association of State Highway and Transportation Officials (AASHTO) guidelines recommended the use of either the Acid Insoluble (AASHTO) or Polish Test (AASHTO) for evaluating aggregates. Thus, a requirement of a minimum polish value from 45 to 48 and a maximum carbonate content of aggregate from 10 to 25 percent is in accordance with the accepted national and international practice.

2.1.5. Aggregate Factors Affecting Pavement Friction

Excluding those asphalt pavements produced mainly from fine aggregates, the skid-resistant properties of asphalt pavements depend primarily on the coarse aggregates. According to a study by Beaton (1976), four characteristics should be evaluated in the selection of aggregates for skid-resistant asphalt pavements: texture, shape, size, and resistance to polish-wear action. Texture was discussed in previous section, the other three characteristics (i.e., shape, size, and resistance to polish-wear action) are explained below.

2.1.5.1. Aggregate Shape

The shape of an aggregate particle significantly affects its skid-resistant properties. Shape of the aggregates can also influence factors like hardness of grains, strength of the matrix, and overall aggregate resistance to abrasion. Aggregate processing procedures also govern the shape of both natural and synthetic aggregates. Angularity contributes to skid-resistant qualities, but retention of angularity depends on characteristics like mineralogical composition and amount of polish-wear produced by traffic.

2.1.5.2. Aggregate Size and Gradation

Aggregate size can also influence the skid resistance of a pavement , but it must be considered in relation to the pavement type and mix design. In general, larger-size aggregates in asphalt pavement mixes have a greater influence over skid resistance than smaller-size aggregates. As per Dahir et al. (1979), open grading has been successfully used to facilitate fast drainage of wet pavements in the tire-pavement contact area, thus reducing the skid resistance-speed gradient.

2.1.5.3. Resistance to Polish-Wear Action

The ability of an aggregate to resist the polish-wear action of traffic has long been recognized as the most important characteristic for consideration in pavement construction. When an aggregate becomes smooth, it will have poor skid resistance. Also, if it polishes and wears (abrades) too rapidly, the pavement will become slippery under wet conditions (Hosking 1976).

A study by Sherwood and Mahone (1970) showed that coarse grain sizes and differences in grain hardness appear to combine to lead to differential wear and plucking out or shearing of grains that result in a constantly renewed abrasive surface.

According to Shupe (1958), certain minerals are associated with good skid resistance qualities. For example, dolomitic limestone has been shown to have superior polishing resistance and friction properties compared to relatively pure carbonate limestone.

2.2. Frictional Needs of Traffic

Normal needs of traffic encompass all driving, cornering, and braking maneuvers by the majority of drivers under normal traffic conditions. In providing skid resistance, the normal frictional needs of traffic must be satisfied before steps can be taken to accommodate more severe demands. Minimum frictional requirements of a pavement are those that satisfy the normal needs of traffic. “Minimum” refers to the lowest acceptable friction level and specifically implies that the level should be higher whenever possible. Minimum frictional requirements are, therefore, defined if the normal needs of traffic can be described. As outlined in Kummer and Meyer (1967), three methods of determining the minimum frictional requirements are as follows:

1. For any standard skid-resistance measurement method, a comparative study can be made between the skid resistance requirements of different pavement sections. For example, the skid resistance observed on a large sample of pavement surfaces, representing the entire design speed range from 48 to 129 km/hour (30 to 80 mph) can be compared with the skid-resistance measured on other surfaces under clearly defined pavement conditions. This method determines the friction level, which separates pavements susceptible to skidding and skid-resistant pavement surfaces.

2. Driver behavior patterns of a large driver population during acceleration, driving, cornering, and deceleration can be investigated by concealed recorders carried on board or located near the site being surveyed. This method yields an acceleration spectrum, which defines normal, intermediate, and emergency needs according to magnitude and their frequency of occurrence.

3. The frictional needs can be deduced from vehicle design and highway geometry, or from the superposition of the two, whenever the limiting needs are determined by these factors and not by the driver – for instance, by a full-throttle acceleration of a particular type of

vehicle. The frictional needs for this maneuver are solely dictated by vehicle factors such as the weight-to-horsepower ratio, transmission ratios, and the location of the center of gravity of the vehicle.

2.2.1. Factors Affecting Wet-Pavement Safety

Skid number (SN) alone is not a good measure of wet pavement safety. Many other factors affect safety under wet-pavement conditions, and it is only when these conditions demand a particular level of traction that SN becomes important. Some of these factors, as identified by Wambold and Kulakowski (1991), are listed below.

1. Vehicle Speed: Friction demand increases with speed. The centrifugal forces generated during the vehicle cornering, which have to be counteracted by tire-pavement friction forces to prevent the vehicle from skidding off the road, are proportional to the square of vehicle speed. Also, pavement resistance decreases with increasing speed in an approximately exponential manner.

2. Road Geometry: Friction demand on straight sections of a roadway is low, if the road is level, if the vehicles travel at low speeds, and if there are no intersections. The demand for friction increases significantly if a grade or a curve is to be negotiated. Page and Butas (1986) concluded that wet-pavement accident rates are significantly higher on curves than any other type of geometric alignment. The effect of curvature on wet-pavement accident rates was

found to be particularly significant on pavements with SN values less than 25. Furthermore, for SN values less than 25, wet-pavement accident rates were significantly greater for both uphill and downhill slopes steeper than 3 percent than the corresponding accident rates for flatter terrain.

3. Traffic Flow: Traffic volume does not have a significant influence on wet-pavement accident rates. However, under special circumstances, like on undivided highways with SN values less than 25, wet-pavement accident rates increase significantly when average daily traffic exceed 15,000 vehicles. Traffic composition, particularly the percentage of trucks, can have a significant effect on friction demand, since the stopping distances for trucks are 1.3 to 2.8 times longer than those for passenger cars.

4. Vehicle Type: If equal stopping distance is required for all vehicles, then the friction demand for buses and trucks is higher than that for passenger cars. The friction demand is also higher for vehicles with lower degrees of understeer.

5. Driver Skills: Few drivers can operate their vehicles with 100 percent efficiency, i.e., using 100 percent of the available friction. Olson et al. (1984) found that truck driver efficiencies ranged from 62 to 100 percent; however, most drivers had little or no practice in emergency braking situations. The concern over emergency braking skills will be considerably alleviated when antilock brake systems (ABS) become a more common feature.

2.2.2. Skid Resistance Requirements and Practices by Different Agencies

For the sake of uniformity, skid number at 40 mph using a locked wheel skid trailer is normally used to compare the minimum requirements set by different state agencies. The Florida Department of Transportation (FDOT) Safety Improvement Program Manual calls for desirable skid number values of 35 and greater for facilities with posted speed limits greater than 45 mph. On roadways with a posted speed limit less than or equal to 45 mph, the desirable skid number value is 30 or greater. In addition, the FDOT Friction Testing and Action Program calls for skid number values of 35 and above, and pavements having mean skid number values below 35 must be re-tested in one year. These friction requirements are generally consistent with other state transportation departments (Jackson 2003). The Oklahoma Department of Transportation (OKDOT) requires a minimum field skid number of 35 which confirms the previous conclusion, while the New York Department of Transportation (NYDOT) uses a design target of minimum skid number of 32 at a speed of 40 mph using ribbed tires. The Indiana Department of Transportation (INDOT), on the other hand, established a uniform minimum friction requirement of 20 for the standard smooth tire at 40 mph. It was indicated that by the seven-year friction measurements, this friction requirement can guarantee a reasonable and consistent friction performance for INDOT network pavements (Li et al. 2003). One more important thing to mention is that many state highway agencies have established their minimum friction requirements based on the recommendation of the minimum friction requirement by NCHRP-37

(Kummer and Meyer 1967). Using a standard ribbed tire, NCHRP-37 recommended a minimum friction number of 37.

The Texas Department of Transportation (TxDOT) has done extensive research and summarized the guidelines that different State Departments of Transportations follow for testing and acceptance of aggregates for adequate provision of skid-resistant pavements (Jayawickrama and Thomas 1998). The guidelines have been reproduced in the ODOT report by Liang (2003).

2.3. ODOT Research by Larson and Smith

A report by Larson and Smith (2008) has provided information on the relationship between skid resistance numbers measured with ribbed and smooth tire and wet-accident locations. This research was initiated by the Ohio Department of Transportation in 2006 to respond to Ohio's high-crash locations with the following specific goals:

- Reduce crash frequency by 10% by 2015
- Reduce rear end crashes by 25% by 2015
- Reduce the number of annual fatalities to 1,100 by 2008

ODOT has been examining a variety of strategies, such as traffic engineering improvement and road geometric design improvement to realize these goals. In the Larson and Smith study, a total of 90 locations throughout the state were selected to represent three different site categories: signalized intersections, unsignalized intersections, and congested freeways. These site categories were considered to have the most potential to reduce total, and particularly with rear-end crashes.

Some of the main conclusions from this study are enumerated below.

- No single variable, such as SN(64)S or SN(64)R, was found to be a good surrogate for identifying sections needing a skid resistant overlay or for proactively predicting crash rates.

- All of the correlations exhibited low R^2 values, and the multivariate analyses failed to show strong individual correlations for the key variables.

- There is considerable variability in the data, and there are other factors that are not being considered.

- Preliminary recommendations were given to ODOT so that pavement sections with a potentially higher probability of crashes could be identified.

- Guidelines were given to develop a procedure to (1) select sections that need a corrective treatment (Intervention Level), and (2) identify sections where poor friction, macrotexture, or roughness may be contributing to increased total or wet-pavement crash rates (Investigatory Level). These guidelines are reproduced in Table 2–1.

Table 2–1: Recommended intervention (minimum) and investigatory (desirable or target) friction levels for ODOT network level evaluations (Larson and Smith 2008).

Check	Variable	Minimum	Target
1	a. If wet/total crash rate, and	≥35 percent	≥ 25 percent
	b. Annual average number of wet pavement crashes(2 or 3 years average), then	>3 for rural >5 for urban	> 2 for rural >3 for urban
	c. Check minimum SN	$SN(64)R_{min}$ < 32 or $SN(64)S_{min}$ <23	$SN(64)R_{min}$ <42 $SN(64)S_{min}$ <32

2.4. Recent Significant Research Findings

A study by Oh et al. (2010) concerning traffic and environmental effects on skid resistance in California was interesting. This study was based on skid data collected in the California state highway network over the past two decades using a standard locked wheel skid trailer and statistical analyses. Oh et al. indicated that the factors with the largest effects on skid resistance are the age of pavement, average daily traffic (ADT), temperature, precipitation, and the length of the period since the last significant precipitation. They developed a predictive model for skid resistance deterioration.

The main conclusions from this study are as follows:

- SN40 and environmental factors can be significantly correlated. Environmental factors – especially the temperature at the time of measurement, the average precipitation, and the number of dry months since the last significant precipitation – are all important, since the combination of these factors can cause seasonal variation in SN40. Oh et al. recommend that measurement of SN40 should be standardized in order to use SN40 values to prioritize pavement sections maintenance.

- SN40 is inversely related to ADT, and shoulder lanes tend to have lower SN40 compared with the average due to higher truck traffic. Pavement age has also a negative effect on SN40. However, the effect of ADT and shoulder lane is larger than that of age. This fact leads to the following suggestions for data collecting strategies: SN40 should be measured at high-risk sections where ADT is higher, and SN40 should be measured in the shoulder lane to detect possible low values of SN40.

TxDOT has developed several methods to measure aggregate shape, angularity, and texture. In Texas Project 5-1707 (Rezaei, Masad, and Chowdhury 2011), the change of the characteristics of aggregate as a function of polishing time was studied. Subsequently, in Texas Project 0-5627-1

(Masad et al. 2009) and 0-5627-2 (Masad et al. 2010), a new aggregate classification was developed for assessing real-field pavement skid resistance.

There are two primary conclusions form Phase 1 of Project 0-5627 (Masad et al. 2009, 2010): (a) it is possible to control and predict frictional properties of the pavement by selecting the aggregate type and asphalt mixture design, and (b) there exists a strong relationship between mixture frictional properties and aggregate properties. Both conclusions have already been presented independently in Liang (2009).

The Texas study investigated aggregate properties such as aggregate shape characteristics measured using the Aggregate Imaging System (AIMS), British pendulum value, coarse-aggregate acid insolubility, Los Angeles weight loss, Micro-Deval weight loss, and magnesium-sulfate weight loss. The research confirmed that main aggregate properties affecting the mix skid resistance include: the British pendulum value, texture change before and after Micro-Deval measured by AIMS, terminal texture after Micro-Deval measured by AIMS, and coarse-aggregate acid insolubility value.

In the Texas study, a model was developed to predict the initial F(60), terminal F(60), and rate of change of the International Friction Index (IFI) for the mix. Aggregate gradation was characterized by fitting with a cumulative Weibull distribution curve using two fitting parameters κ and λ for shape and scale parameter, respectively. Predictive equations developed by Luce

(2007) were utilized to determine aggregate texture properties. An exponential decaying function was proposed to describe the change of aggregate texture. The TxDOT predictive model was intended to predict mix friction based on gradation and estimate aggregate resistance to polishing using Micro-Deval. The rate of change for IFI was only related to the rate of change in aggregate texture using the texture model developed by Mahmoud (2005). It seemed that the predictive method relied on many different laboratory test methods to determine aggregate texture and friction resistance with polishing time. Furthermore, many assumptions were made in developing the predictive equations, which lack field validation.

3. DEVELOPMENT OF POLISHING MACHINE

3.1. Introduction

With time and traffic, asphalt concrete pavements will gradually lose their skid resistance, creating a serious safety concern – particularly when pavements are wet. As the driving speed and ADT increases, the chances of having skid-related accidents also increase rapidly (Beaton 1976; Brilett 1984). Thus, the FHWA has issued a Wet Skid Accident Reduction Program to encourage each state highway agency to minimize wet-weather skidding accidents by identifying the sections of roadways with a high occurrence of skid accidents and then resurfacing the pavement or rejuvenating the surface texture to bring the asphalt pavement surface to an adequate skid resistance level. However, the cost associated with identifying problematic sections and taking remedial action could be prohibitively high. An attractive approach would be to take a more proactive stand in screening the polishing potential of aggregates and hot mix asphalt to ensure that the selected mix can provide sustained resistance to polishing while providing an adequate level of friction over the life span of the pavement. To achieve this initial screening task during the mix design stage of HMA, there is a need to develop a laboratory scale accelerated polishing machine that can mimic the actual abrasion and polishing behavior between the rubber tire and the HMA surface.

3.2. Existing Laboratory Scale Polishing Devices

As a result of past efforts in developing laboratory-scale accelerated polishing devices, several key mechanisms involved in polishing of aggregates or HMA have been identified. As reviewed in Ibrahim (2007), the skid resistance of asphalt concrete can be affected by bleeding and flushing of bituminous binder to the surface, surface wear due to studded tires, polishing of surface aggregate, rutting due to compaction, lateral distortion, contamination (by rubber, oil, water, etc.), smoothened macrostructure, and inadequate cross slope. Among these factors, however, aggregate and mixture characteristics remain the most dominant controlling factors. Research activities focused on polishing and friction characteristics of aggregates (Colony 1984; Colony 1992; Liang and Chyi 2000; Liang 2003; Dewey et al. 2001; and Do et al. 2003) have shown strong correlations between the time history of skid number (SN) degradation at the monitored pavement sections and the factors such as traffic conditions, properties of asphalt mixes, and geological features (such as the predominant aggregate and the physiographic area). In the research on aggregate friction loss by Liang and Chyi (2000), the aggregate polishing propensity was identified by means of a suite of test procedures, including the use of mineralogical analysis using thin sections and the Acid Insoluble Residue test (ASTM D 3042-03). Thus, the current understanding of aggregate polishing and friction behavior is well established.

A review of the existing laboratory-scale accelerated polishing devices reveals that they can be categorized into three groups: one is capable of polishing the aggregate samples, the second is capable of polishing the HMA samples, and the third is capable of polishing both aggregate and HMA specimens. A brief review of the existing devices is summarized in Table 3–1.

Table 3–1: A summary of the existing accelerated polishing machines.

Device	Strengths	Weaknesses	Specifications
Polishing Devices for Aggregates			
British Polishing Wheel	Accelerated polishing for lab testing. Bench sized.	Used for aggregates only	ASTM D3319
Michigan Indoor Wear Track	Close to real world.	Specimen preparation is cumbersome and time-consuming. Used for aggregate only.	MDOT
Micro-Deval	Effective for polishing aggregates in a short time.	Used for aggregates only	AASHTO T327-05/Tex-461-A
Polishing Devices for HMA			
NCAT Polishing Machine	Sized to match DFT and CTM. Can be used in the lab or in the field.	42 hours to complete the test. Specimen preparation is cumbersome and labor intensive.	NCAT
Polishing Devices for Both			
NCSU Wear and Polishing Machine	No need for water or grinding compounds.	Polishes a relatively small area.	ASTM E660
Wehner/Schulz Polishing Machine	Can conduct polishing and friction measurements	Unable to handle gyratory-compacted specimens.	ASTM E1393
Penn State Reciprocating Polishing Machine	Portable. Can be used in the lab or in the field.	Polishes a relatively small area. Fallen into disuse.	Do et al., 2006

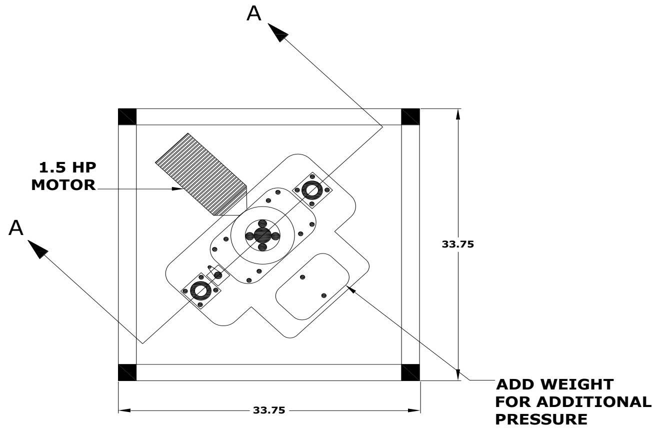
3.3. UA Research Grade Polishing Machine

In this section, the research grade polishing machine developed by Liang (2009) and the operational conditions are briefly discussed.

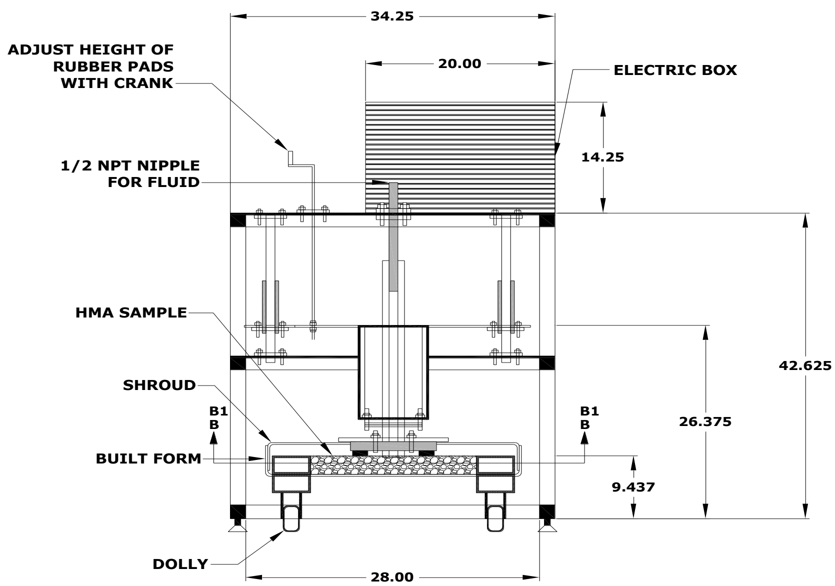
3.3.1. Design Philosophy

The guiding principle in developing the laboratory-scale accelerated polishing machine is to create a device where the evolution history of friction loss of the asphalt pavement surface can be accurately replicated and measured in a short test duration. In essence, the abrasive action between the rubber tire of a vehicle and the asphalt concrete pavement surface should be properly accomplished in the accelerated polishing machine. The design of the UA research grade polishing machine allows for pressing a polishing pad made of styrene-butadiene-rubber (SBR) onto the surface of the HMA specimen at a constant vertical force while rotating the rubber pad at a constant rotational speed. It is noted that the research grade polishing machine can accommodate two specimen dimensions: an 18 inch × 18 inch × 2 inch high roller compacted slab specimen and a 6-inch-diameter by 4-inch-high Superpave gyratory compacted specimen. As a result of having to accommodate different specimen sizes, the rubber pad was designed differently. For the gyratory compacted specimen, a solid rubber disc 6 inches in diameter and 1.5 inch in thickness was used. For the slab specimen, a rubber ring with an approximately 13-inch outside diameter and 9-inch inside diameter was used to fit with the required polishing area for the Dynamic Friction Tester (DFT) and the Circular Texture Measurement (CTM) device.

The schematic diagram of the UA research grade polishing machine is presented in Figure 3–1, in which Figure 3–1(a) and Figure 3–1(b) show the top view and elevation view, respectively. Details of the rubber pad dimension for the gyratory specimen and large slab specimen are shown in Figure 3–1(c) and Figure 3–1(d), respectively. A photograph of the completely fabricated accelerated polishing machine is shown in Figure 3–2(a), and a close-up view of two types of specimens inside the machine is shown in Figure 3–2(b) and Figure 3–2(c), respectively.

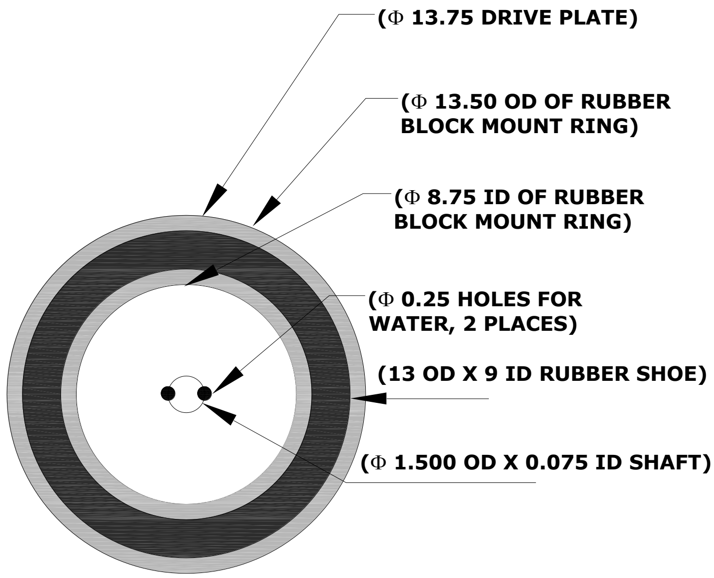


(a) Top view of the accelerated polishing machine using rubber shoes

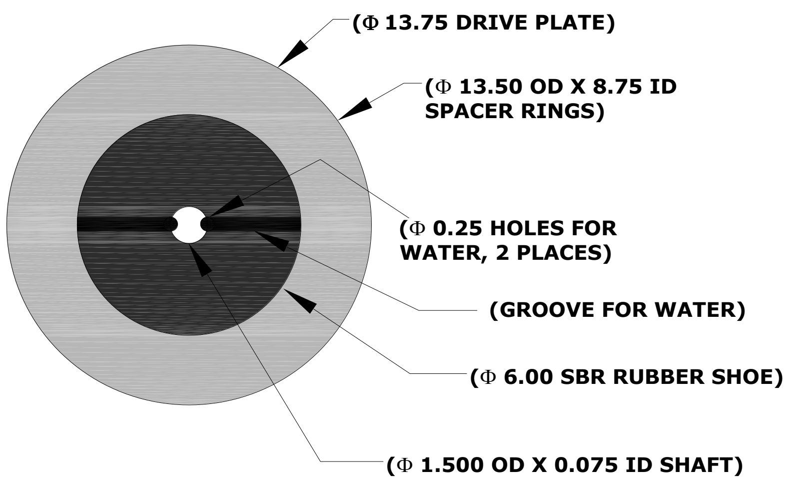


(b) Section A-A for the machine details

Figure 3–1: Different views of the accelerated polishing machine using rubber shoes; all units are in inches.

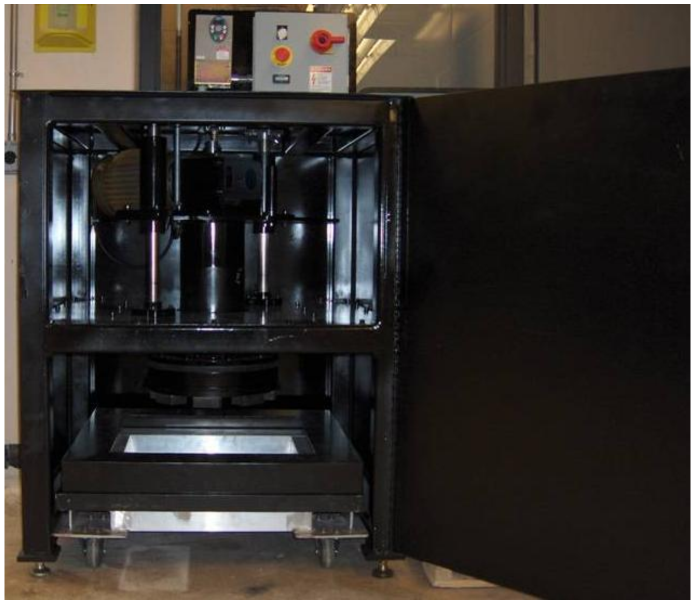


(c) Slab specimen rubber shoe

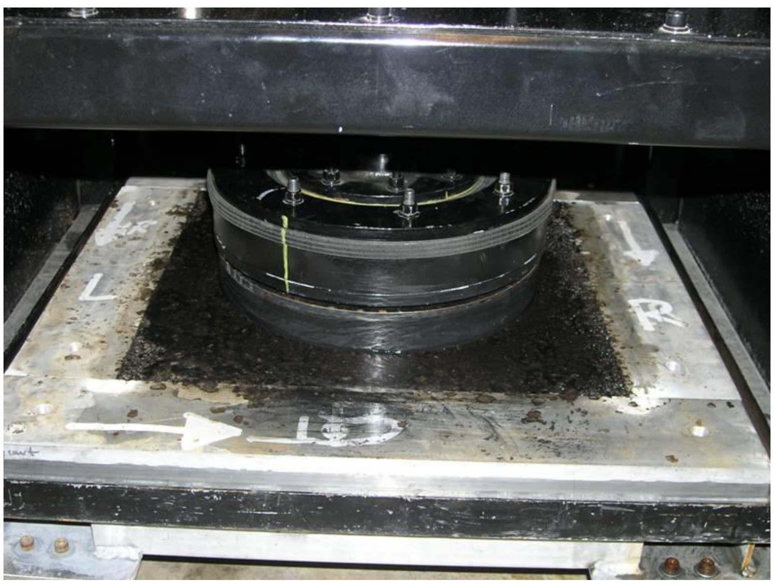


(d) Gyratory specimen rubber shoe

Figure 3–1: Different views of the accelerated polishing machine using rubber shoes; all units are in inches (continued).



(a) Overall view of the accelerated polishing machine using rubber shoes



(b) Details on slab specimen mounting

Figure 3–2: Overall view of the accelerated polishing machine using rubber shoes and setups for testing slab specimen and gyratory compacted specimen.

(c) Details on gyratory compacted specimen mounting

Figure 3–2: Overall view of the accelerated polishing machine using rubber shoes and setups for testing slab specimen and gyratory compacted specimen (continued).

3.3.2. Operating Conditions

The research grade accelerated polishing machine includes separate controls for the vertical force on the specimen, the rotational speed of the rubber pad, and the rate of water spray on the specimen surface during polishing. The range of these individual controls is presented in Table 3–2.

Table 3–2: Range and optimum values for operating parameters.

Operating Parameter	Range	Optimum Value	
		Slab Specimen	Gyratory Compacted Specimen
Rubber Shoe	90 Durometer SBR Rubber	90 Durometer SBR Rubber	90 Durometer SBR rubber
Vertical Force	0 to 400 lb	185 ± 20 Lb	280 ± 10 Lb
Rotational Speed	20 to 350 rpm	30 ± 6 rpm	30 ± 3 rpm
Water Feeding Rate	0 to 500 ml/min	200 ± 10 ml/min	100 ± 5 ml/min

Liang (2009) provides recommended operational conditions for the machine. The recommendation was reached by conducting a series of tests on the HMA specimens using different combinations of operation conditions, including the type of rubber to be used for the rubber pads, the rotational speed of the rubber pad, the vertical force applied by the rubber pad to the HMA specimen, and the rate of water spray. The final selected operation conditions are summarized in Table 3–2. These operation conditions can ensure that the rubber pad does not experience a rocking motion, and that a relatively flat contact surface between the rubber pad and the specimen can be maintained. Furthermore, a water spray was incorporated in order to ensure that any rubber debris can be washed off and that the rubber and HMA specimens do not overheat.

3.3.3. Validation of the Research Grade Polishing Machine

In this section, the repeatability of the research grade accelerated polishing machine, as reported in Liang (2009), is presented for completeness of this report. Furthermore, the ability of the polishing machine to discern the polishing trend of aggregate was demonstrated by comparing the polishing behavior of the aggregate to the polishing behavior of the HMA made using the same aggregate source (Liang 2009).

3.3.3.1. Materials Used in the Validation Study

In the evaluation study of the research grade accelerated polishing machine, two aggregate sources (limestone and gravel) and two asphalt binder grades (PG 70-22 and PG 64-22) were used to prepare the HMA specimens. The gradation curve for the aggregate is shown in Figure 3–3. The optimum binder content was determined by using a Marshall mix design method. The optimum binder content was 5.9% for the mix consisting of limestone and PG 70-22 binder and 6.3% the mix consisting of gravel and PG 64-22 binder.

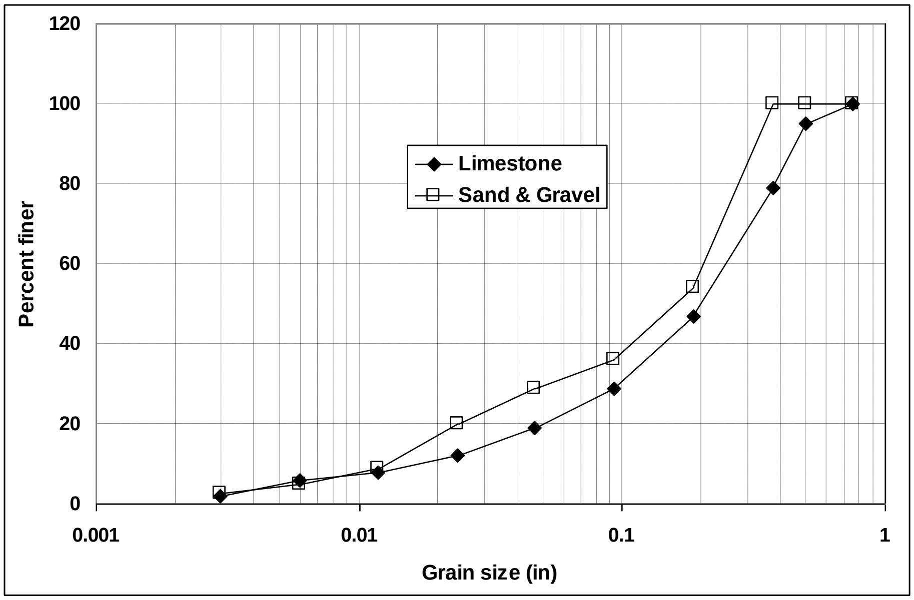


Figure 3–3: Gradation curves for aggregates.

3.3.3.2. HMA vs. Aggregate

In a previous study (Liang and Chyi 2000), various aggregates sources were tested for polishing and friction behavior using the accelerated British Polishing Wheel (ASTM D-3319). The results of polishing behavior of two aggregates from Liang and Chyi (2000) and the polishing behavior of the HMA specimens made with the same two aggregate sources are statistically compared in Table 3–3 and Table 3–4 for limestone and for sand and gravel aggregates, respectively. It can be seen that the polish (friction) values of the aggregates, denoted by *PV*, are highly correlated to the friction values of the HMA made with the same aggregates, denoted by either *BPN* for the gyratory compacted specimens or *FN_SPEED* (where *SPEED* refers to the friction at that measuring speed) for the roller compacted slab specimens with friction measured at different speeds. The fact that aggregates constitute more than 90% by weight of the HMA leads us to believe that aggregate would be a dominant controlling factor on friction of HMA surfaces. The high correlations presented in Table 3–3 and Table 3–4 support this observation. Based on the analysis of variance (ANOVA) results presented in Table 3–3 and Table 3–4 for the limestone and for the sand and gravel aggregates, respectively, the overall significance of the models as indicated by the F-value (i.e., as *F* goes up, *P* goes down, thus indicating more regression confidence in that there is a difference between the two means) and the P-value (the probability of getting a value of the test statistic as extreme as or more extreme than that observed by chance alone, if the null hypothesis H_o, is true) is found to be significant at the 0.05 significance level. Based on the comparisons presented in this section, the laboratory-scale, research grade, accelerated polishing machine is capable of polishing the HMA surface and producing a similar trend as that produced by the British Wheel polishing of aggregates.

Table 3–3: Simple linear regression between aggregate friction values (Liang and Chyi 2000) and HMA friction values (Liang 2009) for Columbus Limestone.

Correlation Variables	**Model Equation**	**R^2 (%)**	**ANOVA Table**	
			F-value	**P-value**
PV vs. BPN	PV = 8.322 + 0.462 BPN	91.6	76.04	<0.0001
PV vs. FN_0	PV = 19.112 + 0.257 FN_0	92.0	80.17	<0.0001
PV vs. FN_10	PV = 19.516 + 0.347 FN_10	95.8	160.84	<0.0001
PV vs. FN_20	PV = 10.688 + 0.649 FN_20	93.9	107.34	<0.0001

Table 3–4: Simple linear regression between aggregate friction values (Liang and Chyi 2000) and HMA friction values (Liang 2009) for Stocker Sand & Gravel.

Correlation Variables	Model Equation	R^2 (%)	ANOVA Table	
			F-value	P-value
PV vs. BPN	PV = -22.166 + 0.876 BPN	98.5	259.35	<0.0001
PV vs. FN_0	PV = -22.956 + 0.603 FN_0	72.7	10.64	0.0310
PV vs. FN_10	PV = -8.717 + 0.574 FN_10	74.2	11.49	0.0275
PV vs. Fn_20	PV = -117.545 + 2.768 FN_20	92.5	49.08	0.0022

3.3.3.3. Repeatability

The repeatability of the polishing results using the accelerated polishing machine was examined in Liang (2009). For each set of specimens made of the same mix formula (aggregate source, aggregate gradation, optimum binder content, binder type, and compaction method and effort), three replicate specimens were tested. The friction values obtained from the BPT, the MTD measured by the sand patch method, and the image analysis results (exposure area of aggregate in percentage of total sample area, indicated as Agg. %) from the three replicates are statistically analyzed using homogeneity of variance (Levene statistic), one-way analysis of variance (ANOVA), and multiple comparisons to check for the repeatability of test results. Homogeneity of variance and one-way ANOVA are used to check if there is any significant difference between the variances and the means of at least two specimens for each set of specimens (three specimens) made using the same job mix formula (JMF). Multiple comparisons analysis, on the other hand, is used to check if there is any significant difference between the means of different two-specimen combinations of the three specimens made of the same JMF. The software Statistical Package for the Social Sciences (SPSS) was employed for obtaining the statistical analysis results. Table 3–5 provides a summary the statistical analysis results. It can be seen from this table that the difference between the variances and the means of the results – in terms of BPT, MTD, and aggregate exposure area (IA) – for the three replicate specimens is insignificant for all cases when considering the friction values (BPN) and IA and insignificant for the vast majority of the cases when considering the macrotexture values (MTD). Therefore, repeatability of test results using the polishing machine can be relatively assured.

3.3.3.4. Methods of Construction

The friction values of the two types of specimens (slab specimens and 6-inch specimens) each with different method of compaction (i.e., roller compaction vs. gyratory compaction) have been found to be correlated and the coefficients of determination have been found to be significant as can be seen from Table 3–6 and Table 3–7 for limestone and for sand and gravel aggregates, respectively. It is very interesting to note that the correlativity is more significant between *BPN* and *FN_SPEED* at low speeds, (for example, at 0, 6, and 12.5 mph). This high correlation is reasonable, considering that BPT actually measures the friction values at low speed (i.e., at 6 mph). Based on the ANOVA analysis shown in Tables 3–6 and 3–7, the overall significance of the models as presented by the F-value and P-value was found to be significant at the 0.05 significance level.

Table 3–5: Repeatability tests for the limestone and gravel.

Aggregate Source	Factor	Homogeneity of Variances		1-Way ANOVA Table		Multiple Comparisons	
		Levene Statistic	Significance[a]	F	Significance[a]	Group	Significance[a]
Possible Medium Polish (Columbus Limestone)	BPN	0.167	0.847	0.280	0.758	1 2	0.982
						1 3	0.853
						2 1	0.982
						2 3	0.755
						3 1	0.853
						3 2	0.755
	MTD	0.384	0.685	5.705	0.009	1 2	0.964
						1 3	0.027
						2 1	0.964
						2 3	0.015
						3 1	0.027
						3 2	0.015
	Agg. %	0.391	0.680	1.501	0.243	1 2	0.312
						1 3	1.000
						2 1	0.312
						2 3	0.305
						3 1	1.000
						3 2	0.305
Possible low Polish (Stocker Sand & Gravel)	BPN	0.484	0.622	1.068	0.359	1 2	0.854
						1 3	0.334
						2 1	0.854
						2 3	0.640
						3 1	0.334
						3 2	0.640
	MTD	0.884	0.426	93.006	0.000	1 2	0.304
						1 3	0.000
						2 1	0.304
						2 3	0.000
						3 1	0.000
						3 2	0.000
	Agg. %	0.121	0.887	0.340	0.715	1 2	0.957
						1 3	0.858
						2 1	0.957
						2 3	0.699
						3 1	0.858
						3 2	0.699

Table 3–6: Simple linear regression between friction values of gyratory compacted specimens and friction values of roller compacted slab specimens using limestone aggregate (Liang 2009).

Correlation Variables	Model Equation	R^2 (%)	ANOVA Table	
			F-value	P-value
BPN vs. FN_0	BPN = 23.686 + 0.550 FN_0	98.7	522.07	0.0000
BPN vs. FN_10	BPN = 25.566 + 0.723 FN_10	97.3	248.48	0.0000
BPN vs. FN_20	BPN = 8.262 + 1.327 FN_20	91.4	74.60	0.0000

Table 3–7: Simple linear regression between friction values of gyratory compacted specimens and friction values of roller compacted slab specimens using sand and gravel aggregate (Liang 2009).

Correlation Variables	Model Equation	R^2 (%)	ANOVA Table	
			F-value	P-value
BPN vs. FN_0	BPN = -4.074 + 0.723 FN_0	81.3	17.38	0.0140
BPN vs. FN_10	BPN = 13.815 + 0.677 FN_10	80.3	16.27	0.0157
BPN vs. FN_20	BPN = -103.208 + 3.056 FN_20	87.8	28.71	0.0059

3.3.3.5. Effect of Air Voids

The effects of air voids of HMA specimens on the measured surface friction properties were examined in Liang (2009). In this section, pertinent findings from Liang (2009) are presented.

For the effects of air voids, the friction measurement was made for the HMA specimens compacted to three different air voids (0.8%, 2.8%, and 5.4%) and polished to three different polishing stages: 0 minutes (initial unpolished stage), 240 minutes (partially polished stage), and 480 minutes (completely polished stage). These air voids were chosen to cover a wide range of realistic densities in pavement during its life span.

The variation of friction with air void in the unpolished, partially polished, and completely polished conditions is plotted in Figure 3-4. At each air void corresponding to a different polishing stage, the average from 12 readings (i.e., 3 specimens $\times 4$ repeated readings) is plotted. It can be seen that the friction value (BPN) increases with an increase in air voids at all polishing stages.

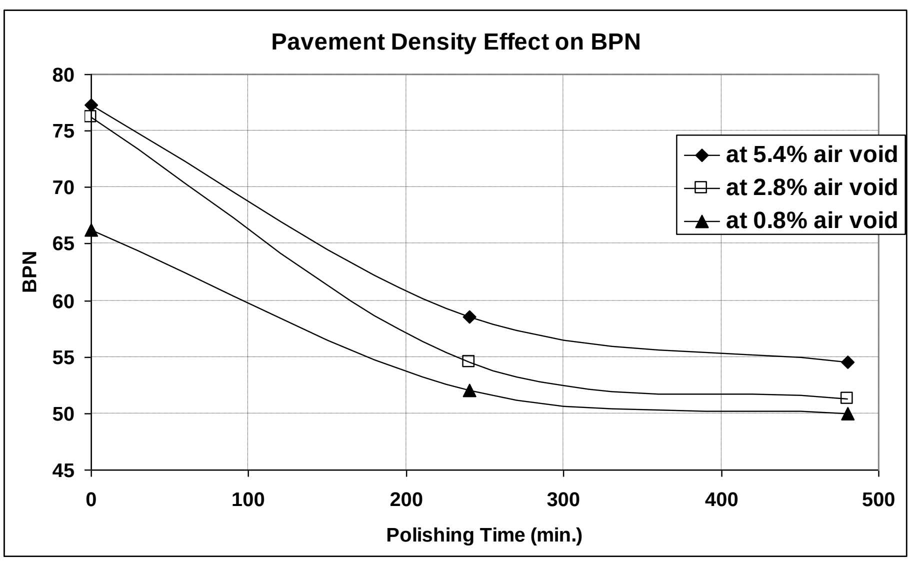


Figure 3–4: BPN vs. polishing time at different air voids.

A set of statistical analysis was conducted using the Statistical Package for the Social Sciences (SPSS) Windows-based program, including homogeneity of variances test, one-way ANOVA, and post hoc tests. Levene's test was used to test if *n* samples would have equal variances (homogeneity of variance). Some statistical tests, for example, the ANOVA, assume that variances are equal across groups or levels. The Levene test was intended to verify the validity of that assumption. A one-way ANOVA test was used to compare the means of several populations. A post hoc test was used to evaluate whether the levels or groups within the factor are significantly different or not; it was performed for factors with three or more levels or groups (Kutner et al. 2004). Table 3–8 provides a summary of statistical analyses performed to support and validate that the effect of changing HMA air voids on the measured friction values at three polishing stages is significant. From Table 3–8 under the column of homogeneity of variances, it can be seen that variances are not significantly different (i.e., equal variances). It is also evident from the one-way ANOVA table that the difference between means is significant. Finally, it can be seen that the mean difference between any two groups is significant for most of the cases, as seen from the column with the heading of multiple comparisons. It is noted that the column “Group” under “Multiple Comparisons” in Table 3-8 refers to the different air voids used; in other words, I denotes air voids of 0.8%, II denotes air voids of 2.8%, and III denotes air voids of 5.4%. All observations are made at the 0.05 significance level.

A useful equation was developed by Liang (2009) to enable the extrapolation of the SN obtained at a given air void to the SN at other air voids. A linear curve fit was developed (as shown in Figure 3–5), where BPN was taken from the intermediate (partially) polished state (after 240 minutes of polishing) that is typical of a pavement that has been in service. The value of the coefficient of determination, R^2, was 0.9967. The slope of the fitting line was 1.4192. Thus, one can deduce the following general equation that relates the BPN at any other air void (BPN_{AV}) to the BPN at measured air void (BPN_{MAV})

$$BPN_{AV} = BPN_{MAV} - 1.419(5 - AV) \tag{3-1}$$

The relationship between SN and BPN, such as the one proposed by Kissoff (1988) and given in Equation 3-2, can be used to convert Equation 3-1 into Equation 3-3

$$SN = 0.862(BPN) - 9.690 \tag{3-2}$$

$$SN_{AV} = SN_{MAV} - 1.223(5 - AV) \tag{3-3}$$

Equation 3-3 can be used to obtain the SN at any air void (SN_{AV}) from the SN at the measured air void (SN_{MAV}) and vice versa.

Table 3–8: Test of homogeneity of variances, one-way ANOVA table, and multiple comparisons for the effect of HMA air voids on BPN (Liang 2009).

Variable	Polishing Stage	Homogeneity of Variances		1-Way ANOVA Table		Multiple Comparisons	
		Levene Statistic	Significance[a]	F	Significance[a]	Group	Significance[a]
BPN	Unpolished	0.310	0.745	859.4	0.000	I, II	0.033
						I, III	0.000
						II, I	0.033
						II, III	0.000
						III, I	0.000
						III, II	0.000
	Partially Polished	0.444	0.661	43.0	0.000	I, II	0.003
						I, III	0.000
						II, I	0.003
						II, III	0.028
						III, I	0.000
						III, II	0.028
	Completely Polished	0.414	0.679	26.8	0.001	I, II	0.005
						I, III	0.001
						II, I	0.005
						II, III	0.200
						III, I	0.001
						III, II	0.200

a. The difference is significant at the 0.05 level.

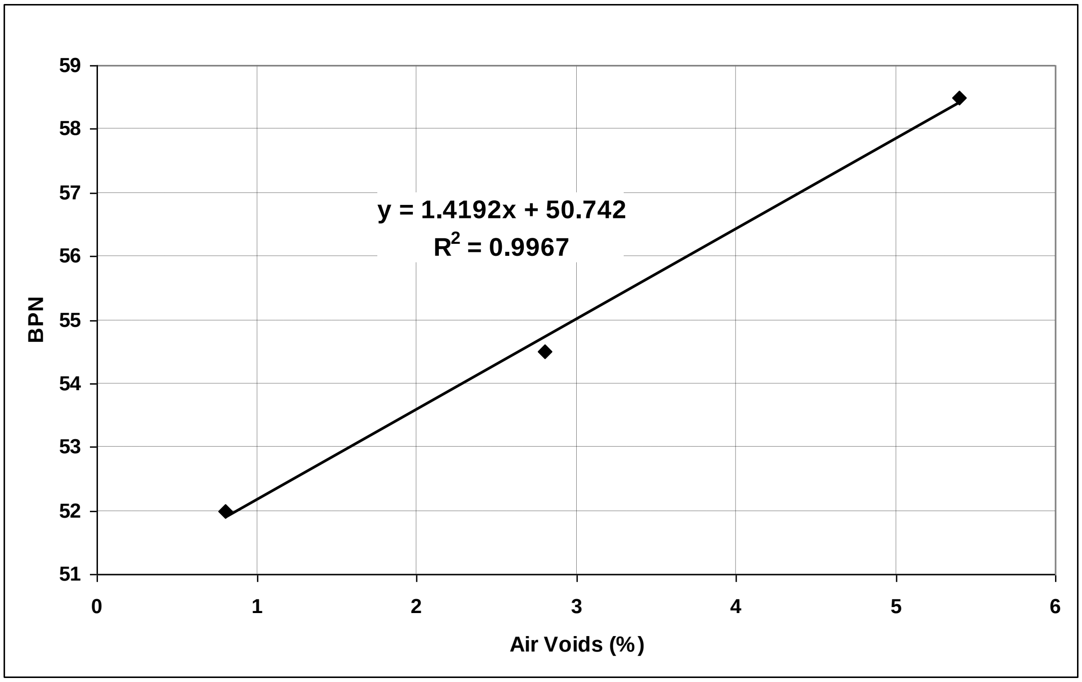


Figure 3–5: BPN vs. air voids (Liang 2009).

3.3.3.6. Summary Remarks on Research Grade Polishing Machine

A research grade, laboratory-scale polishing machine was developed and validated in Liang (2009) to provide accelerated polishing action to HMA surfaces, mimicking the polishing action of a vehicle tire on a pavement surface. The main purpose of this polishing machine was to provide a laboratory test capability to screen aggregate source and mix design to ensure adequate friction (or skid resistance) over the expected life span of an asphalt pavement surface. The research grade polishing machine can polish HMA at two sample sizes: 18 inch × 18 inch × 2 inch high slab specimens compacted using the roller compactor and 6-inch-diameter × 4-inch-high gyratory compacted HMA specimens. The design principles of the polishing machine, together with the operating conditions, were presented in this section. For completeness, evidence for the repeatability of the polishing machine and its ability to capture aggregate polishing characteristics were extracted from Liang (2009) and presented herein. Specific remarks can be made as follows:

1. Repeatability of the polishing machine was checked and affirmed using a one-way ANOVA test.

2. The polishing ability of the machine was confirmed through examination of the test results conducted on limestone and sand and gravel aggregates.

3. Good correlation of the polishing and friction behavior was found between aggregate specimens and the HMA specimens made with the same aggregates.

4. Good correlation was found between the two specimen sizes using different compaction methods.

5. Effects of air voids of HMA on the measured surface friction values were examined, and a semi-empirical equation was recommended for the adjustment of friction values based on air voids of the sample.

3.4 Tentative Acceptance Criteria using UA Research Grade Polishing Machine

A set of tentative acceptance criteria of gyratory compacted HMA specimens was developed by Liang (2009) by using two different correlations (i.e., by correlating BPN with PV or correlating BPN with SN). These acceptance criteria are divided into two parts based on the aggregate type used (i.e., limestone or gravel). The acceptance criteria consist of four categories: (1) highly acceptable, (2) acceptable, (3) marginally acceptable, and (4) unacceptable. This set of tentative criteria could be used to screen and select the appropriate aggregate source and HMA mix design.

In order to use the test results from the developed accelerated polishing device in screening the aggregate source and mix design, there is a need to correlate the friction values measured on the HMA surface in the laboratory to the friction values measured either on the aggregate samples in the laboratory or the skid number measured on the pavement surface. This is because there are more experiences in using either the PV values determined from British pendulum test or SN determined from a locked wheel skid trailer. In this section, different paths will be developed to allow the use of the developed accelerated polishing device for qualifying the aggregate source and mix design from the polishing and friction point of view.

3.4.1. Correlation with Polishing Values

TxDOT has adopted the criteria presented in Table 3–9 for acceptance of aggregates. These standards were based on the polishing values (PV) and the ADT.

Through the developed correlation between aggregate PV from a previous study (Liang and Chyi 2000) and gyratory compacted HMA friction numbers (BPN, shown in Table 3–3 and 3–4), the TxDOT criteria based on PV values can be transformed to represent acceptance criteria of HMA based on BPN values. The derived acceptance criteria, based on BPN values of HMA surfaces, are shown in Table 3–10. Accordingly, four categories of acceptance criteria can be formulated.

1. Highly acceptable (BPN greater than 51 for HMA prepared using limestone aggregate and 62 for HMA prepared using gravel aggregate).

2. Acceptable (BPN greater than 47 for HMA prepared using limestone aggregate and 60 for HMA prepared using gravel aggregate).

3. Marginally acceptable (BPN greater than 43 for HMA prepared using limestone aggregate and 57 for HMA prepared using gravel aggregate).

4. Unacceptable (BPN less than 43 for HMA prepared using limestone aggregate and 57 for HMA prepared using gravel aggregate).

Table 3–9: TxDOT acceptance criteria for aggregates.

Present ADT or Type of Highway	Minimum Required PV
Below 750	No requirements
750 – 2000	28
2000 – 5000	30
5000 - above	32

Table 3–10: Derived acceptance criteria for HMA based on BPN values.

Present ADT or Type of Highway	Minimum Required PV of Aggregate (TxDOT Criteria)	Minimum Required BPN of HMA for Limestone Aggregate	Minimum Required BPN of HMA for Sand and Gravel Aggregate
Below 750	No requirements	No requirements	No requirements
750 – 2000	28	43	57
2000 – 5000	30	47	60
5000 - above	32	51	62

3.4.2. Correlation with SN Values

Friction values measured by the British pendulum tester (BPN) and skid numbers measured by the skid trailer (SN) do not correspond exactly; nevertheless, Kissoff (1988) has developed an approximate relationship (see Equation 3-4) that could be used to relate BPN to SN:

$$SN = 0.862(BPN) - 9.690 \tag{3-4}$$

Therefore, the above acceptability criteria based on BPN values can be altered according to Kissoff's relationship to develop SN-based acceptability criteria as summarized below. The derived acceptance criteria, based on SN values of HMA surfaces, are shown in Table 3–11. Accordingly, four categories of acceptance criteria can be formulated.

1. Highly acceptable: SN greater than 34 for HMA prepared using limestone aggregate and 44 for HMA prepared using gravel aggregate.

2. Acceptable: SN greater than 31 for HMA prepared using limestone aggregate and 42 for HMA prepared using gravel aggregate.

3. Marginally acceptable: SN greater than 27 for HMA prepared using limestone aggregate and 39 for HMA prepared using gravel aggregate.

4. Unacceptable: SN less than 27 for HMA prepared using limestone aggregate and 39 for HMA prepared using gravel aggregate.

Table 3–11: Derived acceptance criteria for HMA based on SN values derived from BPN.

Present ADT or Type of Highway	Minimum Required PV of Aggregate (TxDOT Criteria)	Minimum Required SN of HMA for Limestone Aggregate	Minimum Required SN of HMA for Sand and Gravel Aggregate
Below 750	No requirements	No requirements	No requirements
750 – 2000	28	27	39
2000 – 5000	30	31	42
5000 - above	32	34	44

It is noted that the acceptance criteria outlined in this section was originally developed by Liang (2009) based on the research grade polishing machine. There are several noted shortcomings: (a) the criteria were based on TexDOT experiences that are not necessarily applicable to Ohio, and (b) the tentative criteria relied heavily on the correlation relationships. Therefore, a new method for evaluating HMA samples for friction and polishing is proposed; the methodology is presented in Appendix E.

3.5. UA Production-Grade Polishing Machine

Based on the success of the research grade polishing machine, it was determined by ODOT that an industrial grade polishing machine should be manufactured as a production level machine for the ODOT Office of Materials Management asphalt lab and other labs. Some of the design requirements for the production grade polishing machine are outlined below.

3.5.1 Design Guidelines

The following design guidelines were incorporated into the production grade polishing machine:

- The production-grade polishing machine includes a steel cabinet approximately 34” wide × 24” deep × 32” high. The machine is designed to be set on an in-house steel frame table or a suitable sturdy surface for ease of installing samples and operating the unit. The front cabinet panel includes provisions for a control box, an access door with a polycarbonate window, and an adjustable water flow meter. Base levelers with antiskid pads are included. The top section houses a motor plate, motor, gear drive, load weight, water regulator, and electric actuator to raise and lower the polishing pad. The bottom section includes the polishing pad, the removable water collection basin with drain, and the sample clamp arrangement.

- The machine is designed to polish a 6-inch-diameter × 6-inch-long or a 6-inch-diameter × 4-inch-long cylindrical asphalt sample on one of the flat ends. Samples are secured within the basin using a band clamping arrangement.

- The removable basin includes a weir plate, a filter screen, and a drain. The drain fitting can be connected to an in-house drainage system.

- The polishing pad is a rubber pad approximately 6 inches in diameter and 1.5 inches high. Water feed holes and grooves allow water to be distributed across the sample surface. Because polishing pads are destroyed during the polishing process, the machine is designed so that pads will be easily replaceable.

- The polishing pad is driven by a ¾ horsepower, three-phase, 230-volt totally enclosed fan cooled motor and a 60:1 gear box. A 1.25-inch diameter hollow stainless steel drive shaft is used. The pad is secured to the shaft via a semi-flex arrangement with a taper type hub and collar. The pad rotates at approximately 30 rpm. There are no provisions for varying the speed at the test location.

- The polishing pad is raised and lowered by an electric actuator. The actuator allows for a minimum of 4” of travel.

- Two linear bearing assemblies utilizing 1 inch rods are used to guide the motor plate while traveling vertically and to resist torque during polishing.

- The machine is plumbed to accept tap water for lubricating the sample during polishing. A water system feed line enters the cabinet side panel. The system includes a regulator, valve, and a water flow meter with flow adjustment. The flow meter is located on the front cabinet panel. Water is directed to the top of the drive shaft, where it falls by gravity through the drive shaft center to the pad. The design water flow is 100 ml/minute.

- Weights will be secured to the motor plate to produce the 280 lbs. loading on the sample. There are no provisions for varying the weight at the test location.

- An electrical control box is built into the front panel. A breaker, power on light, auto/manual switch, auto start button, motor on/off switch, raise/lower switch, emergency stop, and operating cycle time meter are included. A safety switch in the door prevents operation of the machine with the door open. The cycle may be run either manually or automatically. The automatic cycle includes turning the drive motor on and off and lowering and raising the polishing pad. The water should be turned on prior to testing and should be run continuously during the test to ensure that the water is flowing freely. A 60-minute cycle time will be set, but this may be adjusted if needed.

3.5.2. Functionalities of the Production Grade Polishing Machine

A production grade polishing machine with the model name "the Polisher" was developed and manufactured by J.M. Parish Enterprises LLC of Barberton, Ohio (located at 95 16th St SW, Barberton, OH 44203; phone 330-321-5090). An operations manual for "the Polisher" machine is provided in Appendix A.

A very brief description of “The Polisher” machine is presented herein. As shown in Figure 3–6, the external view of the machine shows a control box/control panel (labeled as part 2) and an access door (labeled as part 3). A safety lock was provided to prevent the machine from operating unless the door was closed. Figure 3–7 shows a view of the polishing chamber. It reveals the following parts: (1) the chamber, (2) sample tray, (3) particle trap, (4) T-bolt band clamp, (5) sample, (6) water supply and shut off valve, (7) shaft assembly, (8) water drain, and (9) quick disconnect coupling. A close-up view of the polishing disc is presented in Figure 3–8, with the following parts labeled in the picture: (1) polishing disc, (2) swivel locks (for holding the polishing disc onto the shaft mounting plate, and (3) mounting plate. A flow meter, shown in Figure 3–9, provides control of the water flow rate for cooling and for washing off debris during the polishing process. A control box/control panel is shown in Figure 3–10. As can be seen, it consists of the following controlling functions: (1) timer, (2) power on light, (3) work light, (4) hand/off/auto switch, (5) manual actuator: load/unload, (6) manual rotation switch, (7) auto mode switch, and (8) control panel lock.

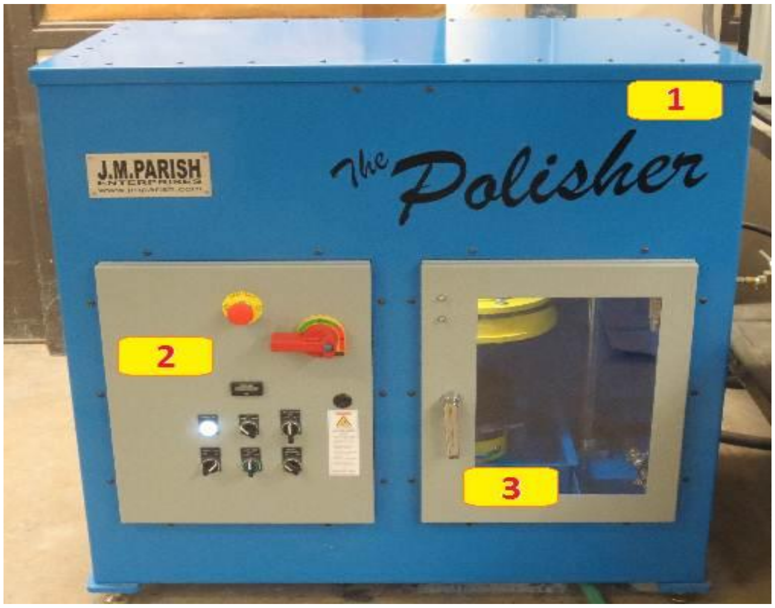


Figure 3–6: Front view of The Polisher.

Figure 3–7: The polishing chamber.

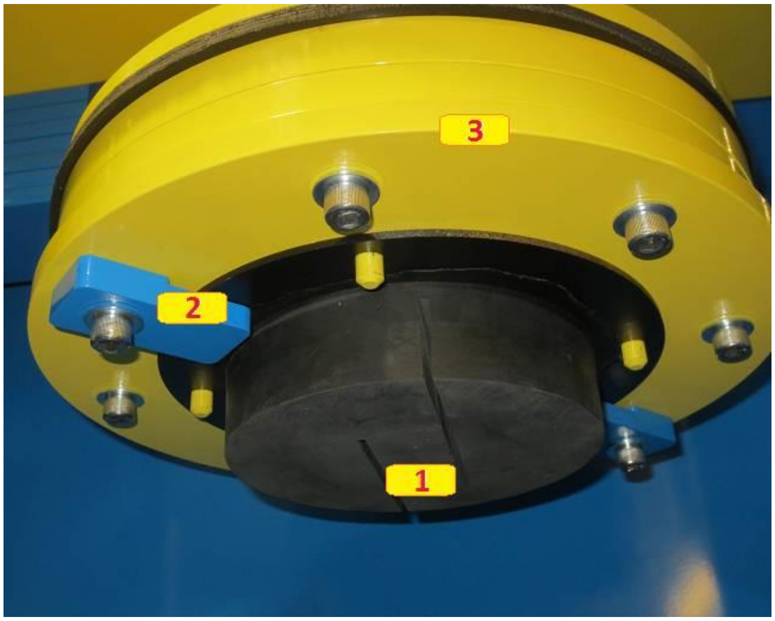


Figure 3–8: The polishing disc.

Figure 3–9: The water flow meter.

Figure 3–10: Control box/control panel.

The operation of "The Polisher" machine is fairly simple and straightforward. The operator is provided with an operation checklist for easy-to-follow instructions. The operation checklist is provided below.

1. Inspect polishing disc;

2. Install sample and clamp the sample in place. Note that Figure 3–11 shows a 6 inch $\times$ 4 inch sample installed with the help of a spacer, while Figure 3–12 shows the 6 inch $\times$ 6 inch sample installed;

Figure 3–11: 6”×4” sample installed.

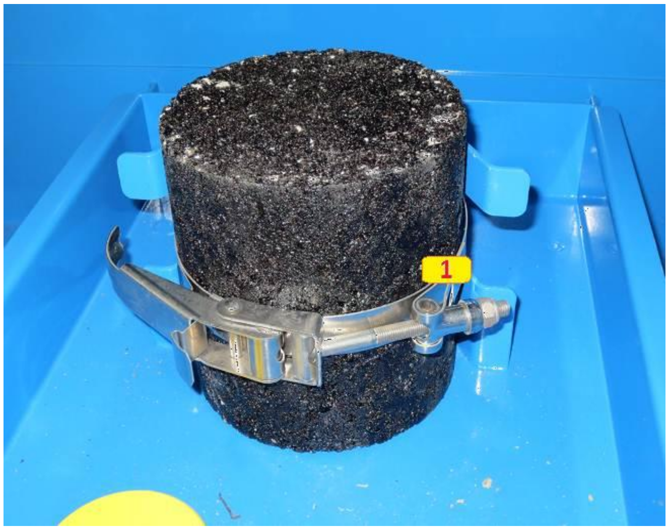


Figure 3–12: 6”×6” sample installed.

3. Inspect that there are no obstacles and set the machine to manual mode to ensure proper setup;

4. Turn water on and set to 100 cc/minute;

5. Inspect flow through polishing disc (see Figure 3–13 for a view of a typical polishing disc;

Figure 3–13: Typical polishing discs.

6. Close access door;

7. Pull emergency stop out;

8. Turn breaker on;

9. Select auto mode. It is noted that auto mode is set for a one-hour polishing period. However, it can be put on hold for a temporary stop during the one-hour polishing action;

10. Select run;

11. Inspect operation through window;

12. After 1 hour, the machine stops;

13. Open door;

14. Remove sample;

15. Turn power and water off;

16. Clean the machine.

3.5.3. Validation of New Polishing Machine

A limited number of tests were conducted to verify that the newly fabricated, commercial grade polisher can work properly according to the design guidelines and that the test results between the new polishing machine and the research grade polishing machine are comparable. To this end, four duplicate samples were provided by ODOT; two of the samples were tested by the research grade machine, and two samples were tested by the commercial grade polishing machine. The test results for all four samples are summarized in Table 3–12. The test procedure and the measurement of BPN are exactly the same for all four samples. For ease of visual comparison, Figure 3–14 shows the test results of two duplicate samples by the research grade machine. Figure 3–15 shows the test results of two duplicate samples by the commercial grade machine. Finally, Figure 3-16 shows the comparison of test results by the research grade and commercial grade machine. Although there were some differences between the two machines, the discrepancy was within an acceptable range.

Table 3–12: BPN Data using Research and Commercial Grade Polishing Machine.

Time (Hr)	New Machine		Average	Old Machine		Average
	Sp1	Sp 2		Sp3	Sp 4	
0	73	77	75	76	77	76.5
1	66	68	67	69	67	68
2	65	65	65	68	65	66.5
3	64	64	64	67	64	65.5
4	64	63	63.5	67	65	66
5	63	60	61.5	65	64	64.5
6	62	59	60.5	63	63	63
7	58	58	58	62	62	62
8	57	58	57.5	60	61	60.5

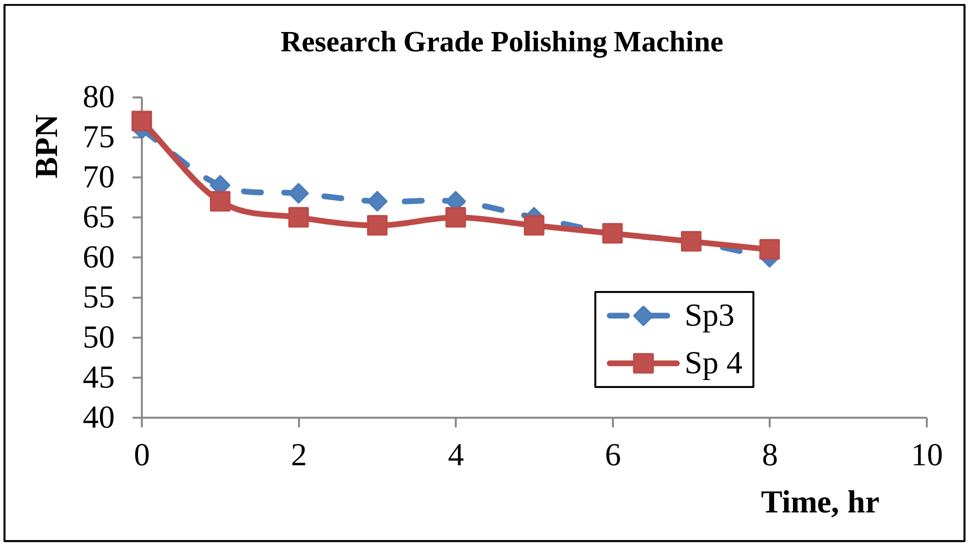


Figure 3–14: Measured BPN vs. polishing time using research grade polishing machine.

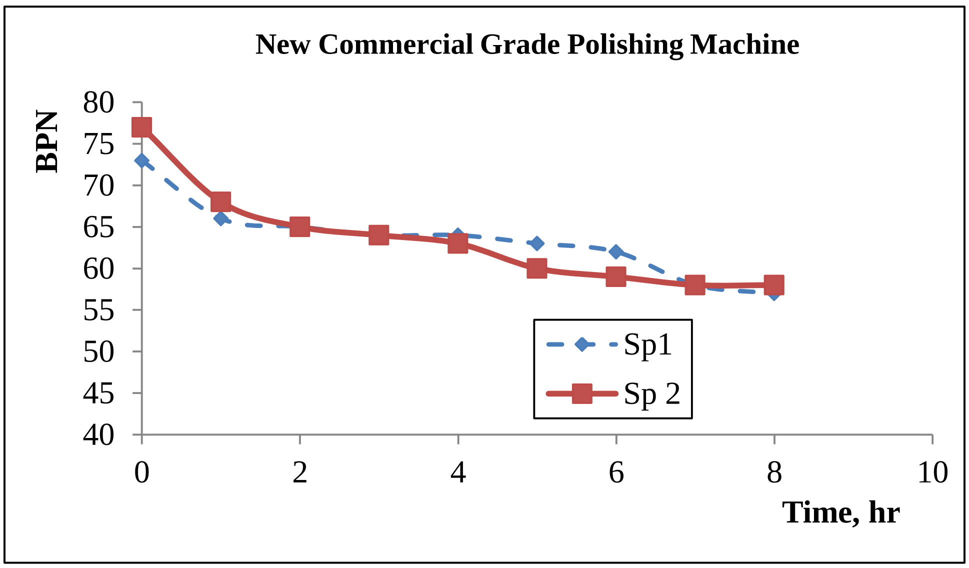


Figure 3–15: Measured BPN vs. polishing time using commercial grade polishing machine.

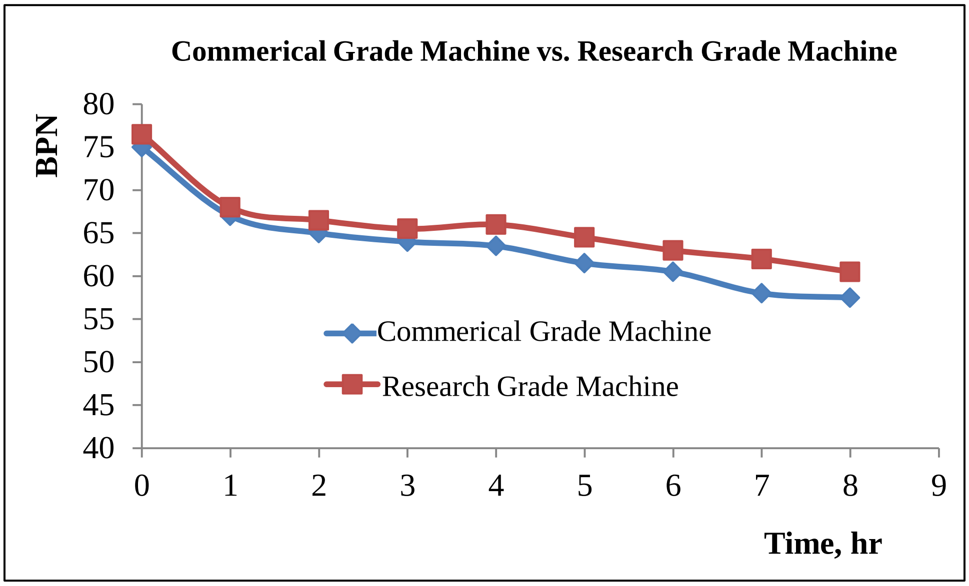


Figure 3–16: Comparison of BPN vs. polishing time between research and commercial grade machines.

3.6. Concluding Remarks

The development of an easy to operate, repeatable, and efficient commercial grade polishing machine for gyratory compacted HMA samples was reported in this chapter. To provide necessary background information and the supporting test results, the first part of this chapter was devoted to presentation of the verification test results of the research grade polishing machine previously reported in Liang (2009). The experiences and lessons learned from this machine provide essential design guidelines for developing the second generation, the so-called commercial grade polisher. The design guidelines were carefully spelled out in this chapter so that any interested entity could fabricate the machine using the same specifications. Finally, the new polishing machine was presented in detail, together with the description of the operation procedure. The verification of the new polisher was presented at the end of the chapter. The new polisher is ready for production applications by commercial test labs and the ODOT OMM asphalt lab.

4. LONG-TERM FIELD DATA COLLECTION

4.1. Introduction

One of the major thrusts of this research was to conduct fieldwork to annually measure friction and texture of six pavement sections over a three-year period from 2007 to 2010. These measured data, together with the data gathered from 2007 to 2008 in a previous research study (Liang 2009), constitute the database from which predictive friction degradation models could be formulated for the in-service pavement conditions. Presented in this chapter is the field measurement program, including the location of pavement sections and the materials used in construction. Although a complete set of raw data pertaining to different measurement devices is provided in Appendix D, condensed measurement results are presented in this chapter in both table and figure format. Finally, observations of data trend and scattering are made at the end of chapter.

4.2. Selection of Pavement Sections

4.2.1. Pavement Sections and Material Properties

Selection of pavement sections for long-term measurements of friction values and surface textures was done in Liang (2009). Eight sections were chosen by ODOT engineers for long-term monitoring following the review of a number of possible locations; for each of these pavement sections, an adequate amount of background information was available regarding the construction materials used and the mix design. Table 4–1 provides information on these identified pavement sections. Based on lab test results using the research grade polishing machine, Liang (2009) classified these aggregate sources roughly into three categories of polishing susceptibility: low (L), medium (M), and high (H). Details of the JMF for each mix design can be found in Appendix B.

Table 4–1: Asphalt concrete pavement sections and the associated JMFs.

Polish Susceptibility	Stockpile	Asphalt Binder	Optimum Asphalt Content (%)	G_{mb}	G_{mm}	Air Void (%)	Nominal Maximum Aggregate Size (in)	Designation
1. Possible low Polish (Gravel)	Stocker Sand & Gravel @ Gnadenhutten	PG 64-22	6.3	2.324	2.390	3.5	0.375	L1
2. Possible Low Polish (Trap Rock)	Ontario Trap Rock @ London	PG 64-22	5.6	2.118	2.618	4.0	0.5	L2
3. Possible low Polish (Gravel)	Martin Marietta @ Apple Grove	PG 64-22	6.3	2.302	2.386	3.5	0.375	L3
4. Possible Medium Polish (Limestone)	Sandusky Crushed @ Parkertown	PG 70-22	5.9	2.352	2.435	3.5	0.5	M1
5. Possible Medium Polish (Limestone)	Sandusky Crushed @ Parkertown	PG 64-22	6.1	2.352	2.452	4.0	0.375	M2
6. Possible Medium Polish (Dolomite)	Stoneco @ Maumee	PG 70-22	5.6	2.451	2.549	4.0	0.375	M3
7. Possible Medium Polish (Dolomite)	Stoneco @ Maumee	PG 70-22M	5.9	2.417	2.521	4.0	0.375	M4
8. Possible High Polish (Limestone)	Chesterhill @ Stockport	PG 64-22	5.6	2.361	2.450	3.5	0.5	H1

4.2.2. Related Lab Test Results

In Liang (2009), the polishing and friction tests on the samples prepared with the same JMF and materials given in Appendix B were performed using the research grade polishing machine. The friction values were measured using the BPT while the texture was measured by the sand patch method. Typically, after each one hour of polishing action in the accelerated polishing machine, the specimen was removed from the polishing machine to measure the friction value (i.e., BPN) and texture properties (i.e., MTD). It should be noted that for each mix type (JMF) studied, a total of three replicate specimens were prepared and tested to ascertain the repeatability of the test results as well as to obtain quantitative data for correlation analysis. Appendix C provides the numerical values of the BPN and MTD for each hour of polishing for all eight hours for the eight different JMFs, labelled according to their polish susceptibility.

4.2.2.1. Discussion of Lab Test Results

Table 4–2 presents the absolute decrease and the percentage decrease in BPN between initial and final values for different HMA mixes. As expected, for low polish susceptibility aggregates, the percent decrease between initial and final BPN is less than medium polish susceptibility aggregates which, in turn, is less than that for high polish susceptibility aggregates. The same conclusion can be drawn when the average absolute decrease and the average percentage decrease for each polish susceptibility aggregate category (i.e., L1, L2, and L3, and M1, M2, M3, and M4, and H1) was calculated.

Table 4–2: Absolute and percent decrease in BPN between initial and final values.

JMF	Initial BPN	Final BPN	ΔBPN	Average ΔBPN	% Decrease	Average % Decrease
L1	73.08	58.67	14.41	14.83	20	20
L2	76.50	59.17	17.33		23	
L3	72.50	59.75	12.75		18	
M1	74.50	54.25	20.25	21.88	27	29
M2	76.67	54.75	21.95		29	
M3	76.75	54.92	21.83		28	
M4	76.08	52.58	23.50		31	
H1	70.50	45.83	24.67	24.67	35	35

Table 4–3 presents the absolute decrease and the percentage decrease in MTD between initial and final values for the different HMA mixes studied. As expected, the percentage decrease between initial and final MTD for low polish susceptibility aggregates was less than that for medium polish susceptibility aggregates which, in turn, was less than that for high polish susceptibility aggregates. The same conclusion can be drawn when the average absolute decrease and the average percentage decrease for each polish susceptibility aggregate category was calculated.

Table 4–3: Absolute and percent decrease in MTD between initial and final values.

JMF No.	Initial MTD	Final MTD	ΔMTD	Average ΔMTD	% Decrease	Average % Decrease
L1	0.88	0.80	0.08	0.23	9	18
L2	1.51	1.03	0.48		32	
L3	0.99	0.86	0.13		13	
M1	1.53	1.14	0.39	0.30	26	25
M2	1.03	0.81	0.22		21	
M3	1.11	0.82	0.29		26	
M4	1.06	0.78	0.28		26	
H1	1.39	0.95	0.44	0.44	32	32

4.3. Field Measurement Program

The field measurement program was designed to measure friction and texture of pavement surfaces at the selected pavement locations. The pertinent information about the pavement sections selected for this study is summarized in Table 4–4, which includes information such as aggregate polish susceptibility (extracted from previous study by Liang and Chyi (2000)) and aggregate source used in each pavement section, the location of the tested pavement section (such as route and section mile marker), and the number of measurement points for each pavement section. At each measurement point, measurements include the skid number, which was measured using the LWST; the friction number, as measured using the DFT; and the mean profile depth, measured using the CTM. In addition, BPN was also measured in the last three years of field work. In general, all field measurements were taken on the left wheel path. The DFT and CTM measurements are the average of two runs on the left wheel path. It is noted that two pavement sections were re-surfaced during the early stage of the research; therefore, the measurement data for these two pavement sections was insufficient for subsequent statistical analysis and model development. The two re-surfaced pavement sections included State Route 7 in District 10 and I-90 in District 12.

Table 4–4: Pavement Sections in Field Program.

Polish Susceptibility	Aggregate Source	District	Location: Route (Section)	No. of Measurements
Existing Pavement Sections				
Possible High Polish (Gravel)	Chesterville @ Stockport	10	007 (37.3-39.0)	8
Possible Medium Polish (Limestone)	Sandusky Crushed @ Parkertown	3	250 (3.55-5.11)	6
Possible Medium Polish (Dolomite)	Stoneco @ Maumee	2	025(15.68-22)	36
Possible Low Polish (Gravel)	Martin Marietta @ Apple Grove	11	250 (22.5-25.5)	10
New Pavement Sections				
Possible Medium Polish (Limestone)	Sandusky Crushed @ Parkertown	3	162 (14.00-19.00)	18
Possible Low Polish (Gravel)	Stocker Sand & Gravel @ Gnadenhutten	11	022(5.00-8.00)	12
Possible Medium Polish (Dolomite)	Stoneco @ Maumee	2	064 (8.90-12.40)	14
Low Polish (Trap Rock)	Ontario Trap Rock @ London	12	090 (28.25-29.21)	6

The sequence of field work at each selected pavement section generally involved three tasks. The first task involved the use of locked wheel skid trailer to measure the skid number at 64 km/hour (40 mph) using the ribbed tire. The second task involved the measurement of the MPD at the same spot of skid number measurement by using the CTM. The third task involved the measurement of the friction number using DFT over the speed range of 0 to 90 km/hour (0 to 55 mph). In carrying out the field work at each selected pavement section, the research team was careful to ensure that the same spots (as close as possible) at each pavement section were used for all three measurements. Further, to minimize the effects of weather-related and traffic-related factors on the measured values, these measurements were conducted at about the same time.

4.4. Field Measurement Results

In this section, field measurement data in a condensed format is presented. As discussed previously, meaningful long-term measurement data is only available for six pavement sections due to the resurfacing of two pavement sections in 2010. The complete raw data for all measuring devices is provided in Appendix D for the six pavement sections: Harrison County, Route 22 (aggregate L1), both east and west bound; Harrison County Route 225 (aggregate L3), both East and West bound; Huron County, Route 162 (aggregate M1), both East and West bound; Huron County Route 250 (aggregate M2), both North and South bound; Lucas County, Route 64 (aggregate M3), both North and South bound; and Wood County, Route 22 (aggregate M4), both North Driving Lane and North Passing Lane.

Tables 4–5 to 4–9 present the measured values for each measurement type over the field program duration. It is noted that some of the measurements summarized in these tables were taken from a previous report (Liang 2009). Table 4–5 provides the average of measurements for SN(64)R. Table 4–6 presents the average of measurements for DFT (20), while Table 4–7 presents the average of measurements for DFT (64). Table 4–8 provides the average of measurements for MPD. Finally, Table 4–9 gives a summary of the average of measurements for BPN.

Some of the pavements were constructed prior to the start of the field measurement program; therefore, the initial values for friction and texture were not available. To determine the initial friction values and texture of pavement surface, the research team took DFT and CTM measurements on the shoulder of the pavement section, with the basic assumption that the shoulder of the road has not been subjected to traffic in the years after installation. These measured data on the roadway shoulders were taken as surrogate for the initial data for the pavement surface in selected sections. In addition, an artificial neural network based approach was used to develop correlations between DFT and SN(64)R. The details of application of the artificial neural network based training techniques for predicting SN(64)R from DFT are described herein.

Table 4–5: Average of measured SN(64)R for different pavement sections.

	Average of observed SN(64)R							
	Direction	Year 0	2007	2008	2009	2010	2011	2012
Harrison R22 constructed at 2006 (L1)	E	58.4	45.9	52.4	52.5	52.4	49.4	56.5
	W	58.4	49.4	54.1	55.4	55.2	51	57.5
Harrison R250 constructed at 2006 (L3)	E	60.4	49.2	53.4	51.1	51.4	48.8	54.1
	W	60.4	47.2	53.5	51	51.2	48.5	55.24
Huron R162 Constructed at 2006 (M1)	E	71.6	61.5	63.2	65.4	62.9	60.9	58.1
	W	71.6	61	65	66.2	64.6	62	62.9
Huron 250 Constructed at 2000 (M2)	N	59.5	36.6	39.8	38.4	41.9	36.9	30.0
	S	59.5	38	40	40.3	41.5	34.3	30
Lucas R64 Constructed at 2004 (M3)	N	69.7	46.7	47.2	45.6	45.7	42.9	43.7
	S	69.7	45.65	47.36	46.94	48.70	42.81	46.33
Wood R25 - Drive Constructed at 2003 (M4)	N	67.4	45.9	51.9	48.0	43.8	44.4	44.3
	S	67.4	46.2	51.3	49.5	42.8	43.7	43.8
Wood R25 - Pass Constructed at 2003 (M4)	N	67.4	53.2	57.5	56.7	51.5	51.1	47.5
	S	67.4	54.8	59.8	59.1	53.6	53.3	50

Table 4–6: Average of measured DFT20 for different pavement sections.

	Average of observed DFT20							
	Direction	Year 0	2007	2008	2009	2010	2011	2012
Harrison R22 constructed at 2006 (L1)	E	0.7	0.650	0.665	0.653	0.669	0.649	0.598
	W	0.7	0.670	0.688	0.665	0.671	0.649	0.621
Harrison R250 constructed at 2006 (L3)	E	0.74	0.603	0.626	0.619	0.618	0.600	0.560
	W	0.74	0.592	0.612	0.602	0.660	0.678	0.600
Huron R162 Constructed at 2006 (M1)	E	0.909	0.737	0.743	0.821	0.794	0.737	0.698
	W	0.909	0.733	0.737	0.818	0.804	0.754	0.738
Huron 250 Constructed at 2000 (M2)	N	0.7	0.424	0.431	0.417	0.400	0.411	0.382
	S	0.7	0.431	0.432	0.390	0.403	0.401	0.366
Lucas R64 Constructed at 2004 (M3)	N	0.817	0.501	0.482	0.470	0.466	0.447	0.344
	S	0.817	0.479	0.479	0.439	0.531	0.529	0.371
Wood R25 - Drive Constructed at 2003 (M4)	N	0.870	0.467	0.471	0.447	0.432	0.419	0.379
	S	0.9	0.460	0.442	0.454	0.425	0.488	0.367
Wood R25 - Pass Constructed at 2003 (M4)	N	0.870	0.596	0.556	0.535	0.522	0.518	0.516
	S	0.900	0.618	0.570	0.546	0.612	0.609	0.445

Table 4–7: Average of measured DFT64 for different pavement sections.

	Average of observed DFT64							
	Direction	Year 0	2007	2008	2009	2010	2011	2012
Harrison R22 constructed at 2006 (L1)	E	0.608	0.52	0.535	0.550	0.525	0.520	0.503
	W	0.608	0.656	0.575	0.633	0.540	0.548	0.518
Harrison R250 constructed at 2006 (L3)	E	0.64	0.493	0.540	0.521	0.521	0.544	0.502
	W	0.64	0.492	0.543	0.513	0.557	0.621	0.492
Huron R162 Constructed at 2006 (M1)	E	0.860	0.544	0.642	0.703	0.702	0.690	0.641
	W	0.863	0.618	0.617	0.698	0.723	0.745	0.707
Huron 250 Constructed at 2000 (M2)	N	0.625	0.356	0.380	0.353	0.327	0.423	0.353
	S	0.626	0.365	0.385	0.318	0.333	0.420	0.300
Lucas R64 Constructed at 2004 (M3)	N	0.816	0.427	0.410	0.447	0.456	0.464	0.317
	S	0.816	0.431	0.432	0.411	0.494	0.499	0.364
Wood R25 - Drive Constructed at 2003 (M4)	N	0.842	0.451	0.450	0.427	0.416	0.410	0.406
	S	0.842	0.442	0.428	0.421	0.409	0.470	0.430
Wood R25 - Pass Constructed at 2003 (M4)	N	0.842	0.554	0.527	0.513	0.509	0.503	0.494
	S	0.842	0.564	0.530	0.512	0.559	0.590	0.436

Table 4–8: Average of measured MPD for different pavement sections.

	Average of observed MPD after discard outliers							
	Direction	Year 0	2007	2008	2009	2010	2011	2012
Harrison R22 constructed at 2006 (L1)	E	0.41	0.495	468	0.505	0.402	0.435	0.383
	W	0.41	0.490	0.472	0.612	0.538	0.513	0.373
Harrison R250 constructed at 2006 (L3)	E	0.717	0.650	0.703	0.778	0.806	0.808	0.784
	W	0.717	0.612	0.704	0.756	0.710	0.765	0.763
Huron R162 Constructed at 2006 (M1)	E	0.743	0.612	0.647	0.604	0.664	0.706	0.6
	W	0.744	0.640	0.653	0.658	0.693	0.778	0.752
Huron 250 Constructed at 2000 (M2)	N	1.260	0.673	0.681	0.623	0.620	0.597	0.720
	S	1.26	0.650	0.680	0.610	0.650	0.697	0.640
Lucas R64 Constructed at 2004 (M3)	N	0.877	0.492	0.497	0.584	0.599	0.614	0.635
	S	0.877	0.506	0.554	0.672	0.709	0.771	0.717
Wood R25 – Drive Constructed at 2003 (M4)	N	0.725	0.578	0.639	0.666	0.758	0.737	0.802
	S	0.725	0.583	0.634	0.673	0.746	0.764	0.67
Wood R25 - Pass Constructed at 2003 (M4)	N	0.725	0.620	0.660	0.681	0.747	0.766	0.718
	S	0.725	0.584	0.610	0.621	0.729	0.652	0.803

Table 4–9: Average of measured BPN for different pavement sections.

	Average of observed BPN							
	Direction	Year 0	2007	2008	2009	2010	2011	2012
Harrison R22 constructed at 2006 (L1)	E	0.837	NA	0.639	0.646	0.608	0.760	0.727
	W	0.837	NA	0.630	0.653	0.667	0.748	0.715
Harrison R250 constructed at 2006 (L3)	E	0.880	NA	0.604	0.640	0.614	0.694	0.670
	W	0.88	NA	0.605	0.562	0.638	0.734	0.66
Huron R162 Constructed at 2006 (M1)	E	0.970	NA	0.707	0.732	0.796	0.804	0.840
	W	0.97	NA	0.700	0.710	0.796	0.837	0.82
Huron 250 Constructed at 2000 (M2)	N	0.830	NA	0.421	0.477	0.473	0.513	0.520
	S	0.83	NA	0.417	0.430	0.480	0.493	0.490
Lucas R64 Constructed at 2004 (M3)	N	0.853	NA	0.509	0.486	0.474	0.497	0.450
	S	0.853	NA	0.501	0.476	0.480	0.513	0.494
Wood R25 – Drive Constructed at 2003 (M4)	N	0.973	NA	0.553	0.530	0.501	0.513	0.512
	S	0.930	NA	0.495	0.441	0.458	0.542	0.500
Wood R25 - Pass Constructed at 2003 (M4)	N	0.973	NA	0.621	0.556	0.538	0.531	0.518
	S	0.930	NA	0.576	0.524	0.597	0.684	0.579

To convert the DFT measurement to SN(64)R by LWST, some statistical methods such as conventional regression analysis and artificial neural network (ANN) were employed to obtain the best correlation. Unlike most traditional statistical methods, the ANN method uses the observed data to build the backbone of the model. Basically, ANN becomes trained from the observed data and builds a mathematical model to predict target values. Figure 4–1 depicts the architecture of the radial basis neural network.

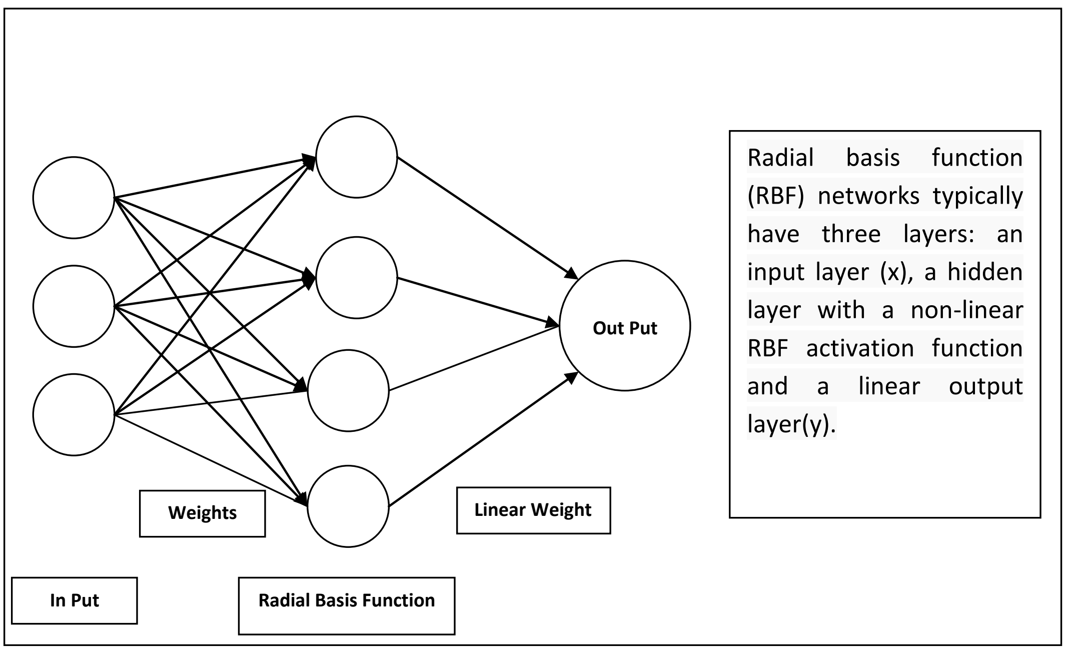


Figure 4–1 Architecture of the radial basis neural network.

To predict SN(64)R for road shoulders, three different types of radial basis neural network techniques have been employed. As shown in Table 4–10, among different neural network algorithms, the design exact radial basis network provided the best performance. Thus, this technique was used to convert the friction number measured by DFT at 40 mph (64 Km/hr) to SN(64)R.

Table 4–10 Summary of different methods to convert DFT measurements to SN.

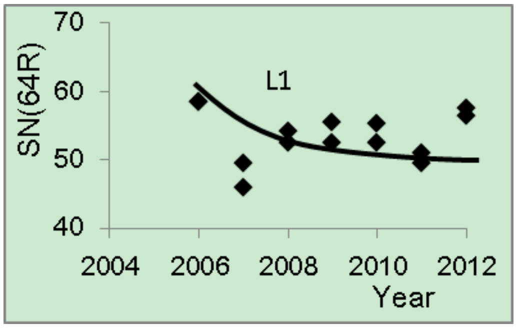
Model used	**R^2**
Generalized Regression Neural Networks (GRNN)	70%
Design Exact Radial Basis Network (NEWRBE)	73%
Design Radial Neural Network (NEWRB)	**83%**
Conventional Linear Regression	73%

4.5. Analysis of Field Measurement Data

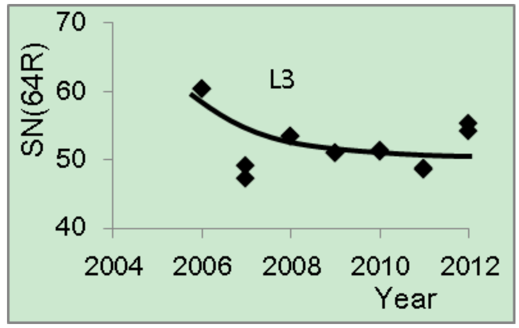
Field measured data discussed in the previous section is plotted in figures to allow for observations of trend. These figures are shown in Figure 4–2 to Figure 4–6, for each of measurement type, including SN(64)R, DFT(20), DFT(64), MPD, and BPN. The general trend can be observed as follows.

- Significant scattering was observed in measured values for all measuring devices. This is expected, given the inherent measurement errors, different months in the year during which the measurements were taken, difficult field conditions for operating the equipment, and the influence of unknown environmental factors, such as precipitation or a dry spell before heavy rainfall within a couple weeks of measurement.

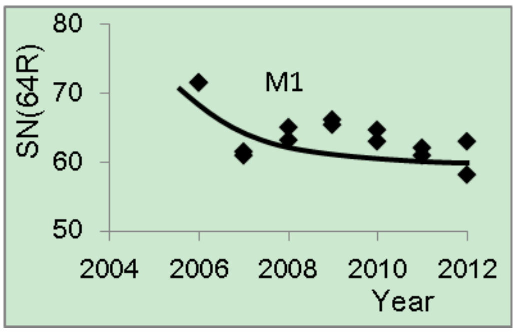
- Significant differences and variations exist between the two driving directions for each pavement section. This could be attributed to different traffic data in each direction or simply to the nature of spatial variability of the measured properties.
- Despite significant scattering and randomness of the measured data points indicated in Figure 4–2 to 4–6, one can observe a rough trend line of friction degradation with time. This decaying trend can be observed for all friction measurements, such as SN, DFT, and BPN. Similarly, this degradation behavior can be observed for MPD.
- It does not make meaningful sense to develop correlations between different friction values measured with different measurement devices. The International Friction Index (IFI) has been considered as a harmonizing property to report friction values. ODOT is also considering migrating toward the adoption of IFI in reporting skid resistance, rather than the use of traditional SN.



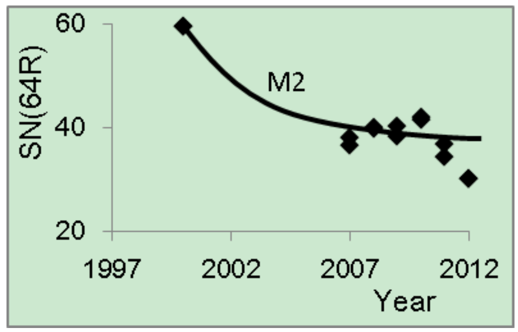
SN(64)R—L1



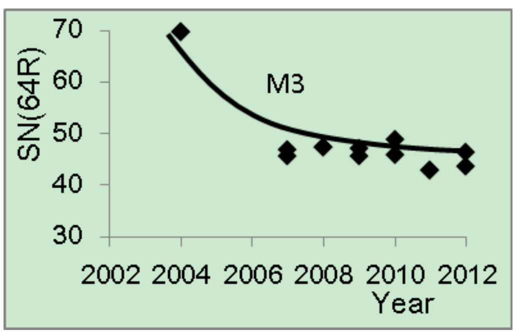
SN(64)R—L3



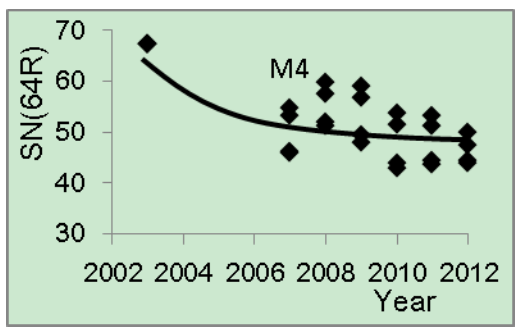
SN(64)R—M1



SN(64)R—M2

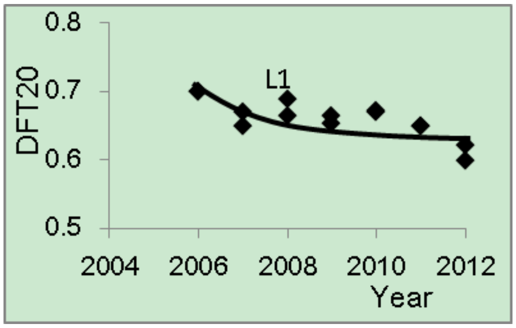


SN(64)R—M3

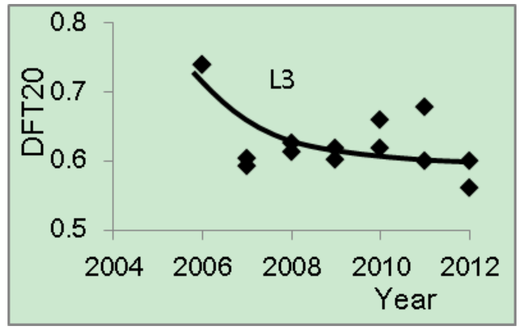


SN(64)R—M4

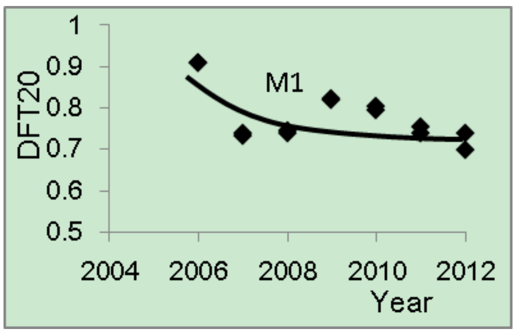
Figure 4–2: A trend plot of SN(64) with in-service years for six pavement sections.



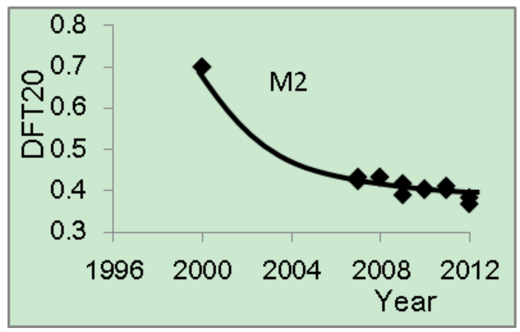
DFT20—L1



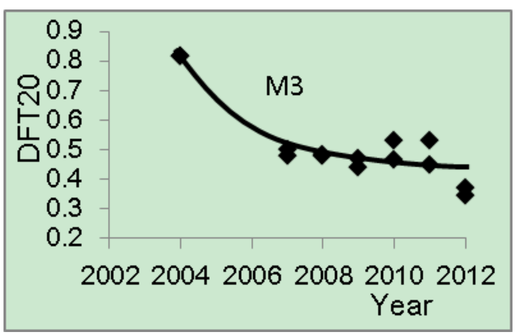
DFT20—L3



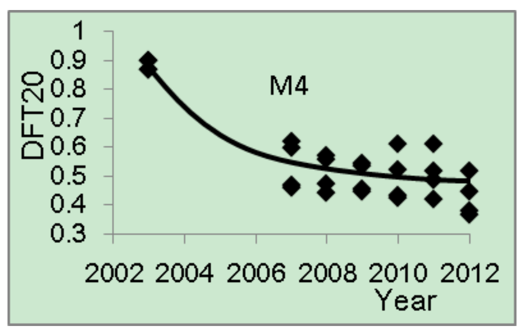
DFT20—M1



DFT20—M2

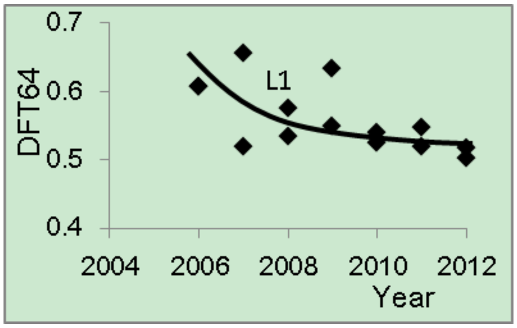


DFT20—M3

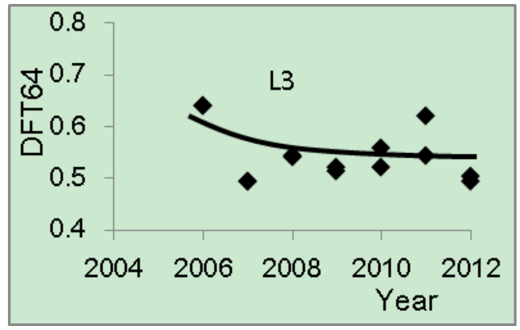


DFT20—M4

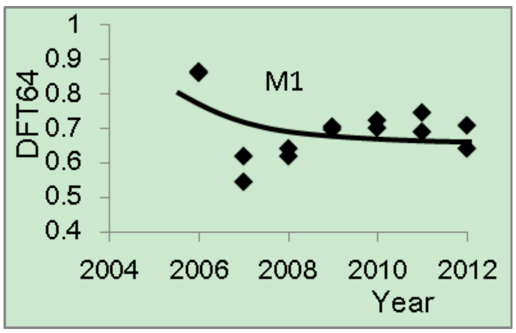
Figure 4–3: A trend plot of DFT20 with in-service years for six pavement sections.



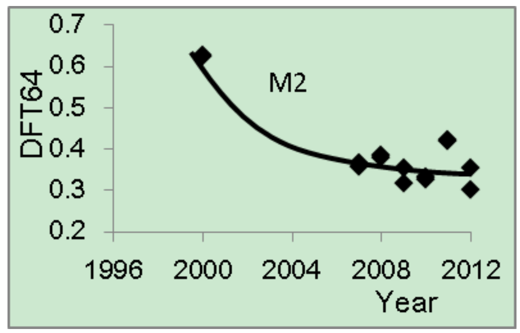
DFT64—L1



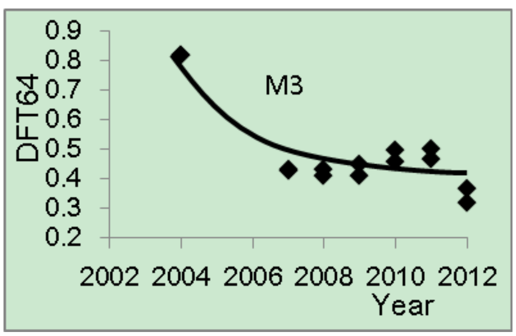
DFT64—L3



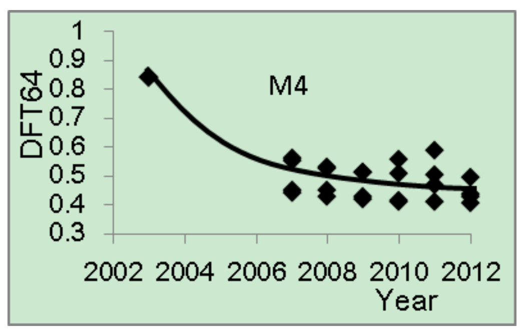
DFT64—M1



DFT64—M2

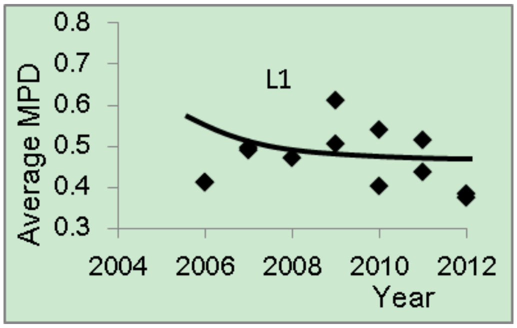


DFT64—M3

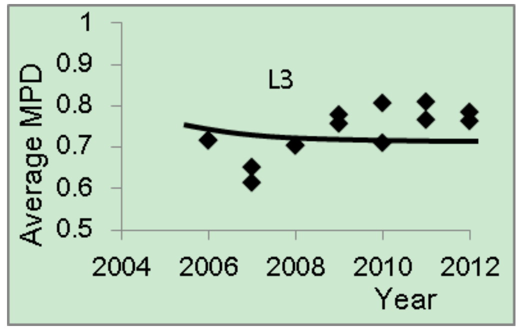


DFT64—M4

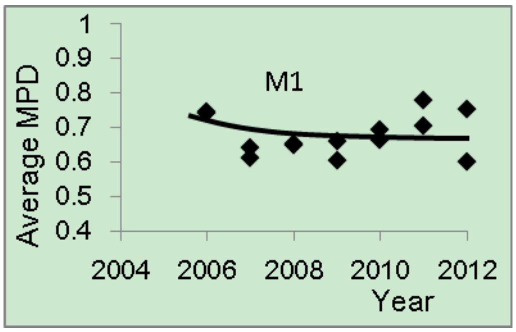
Figure 4–4: A trend plot of DFT64 with in-service years for six pavement sections.



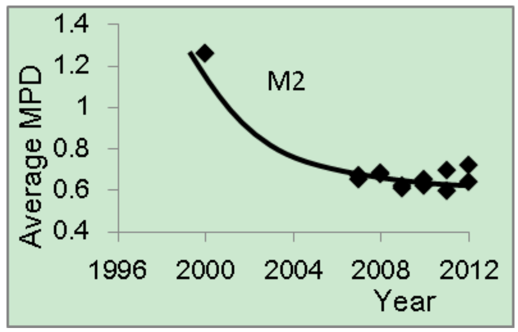
Average MPD—L1



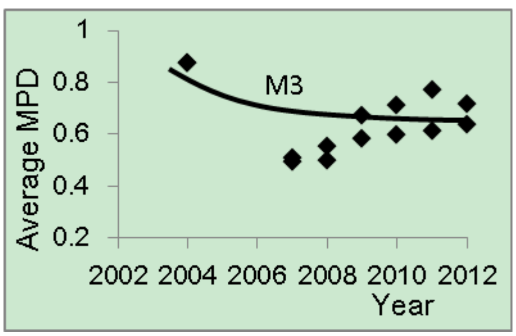
Average MPD—L3



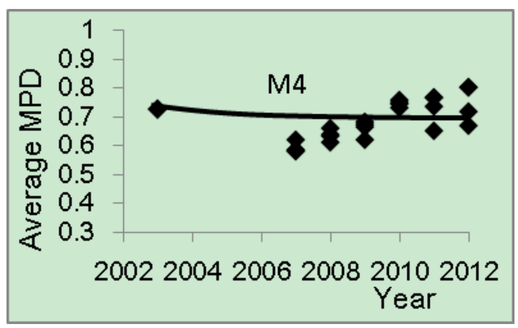
Average MPD—M1



Average MPD—M2

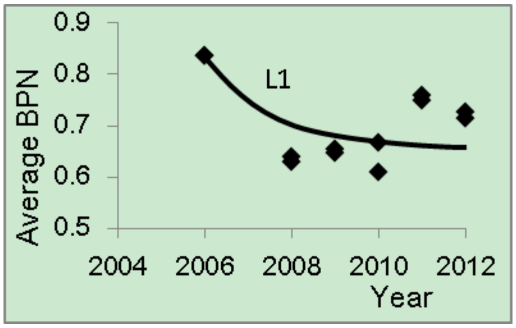


Average MPD—M3

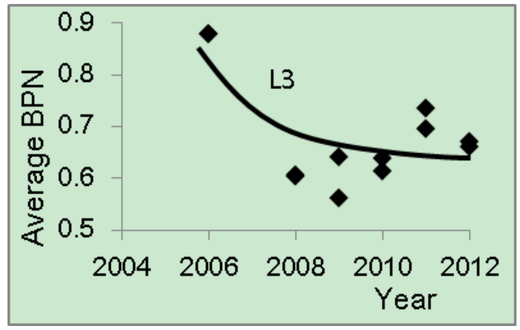


Average MPD—M4

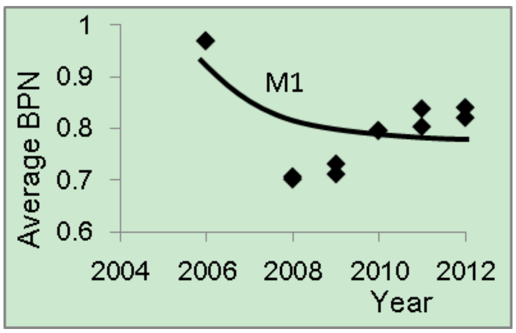
Figure 4–5: A trend plot of average MPD with in-service years for six pavement sections.



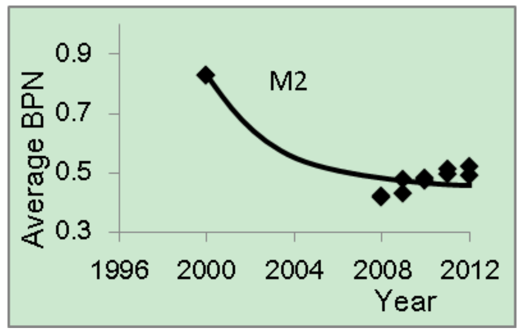
Average BPN—L1



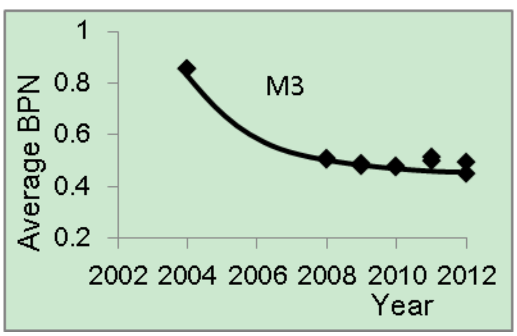
Average BPN—L3



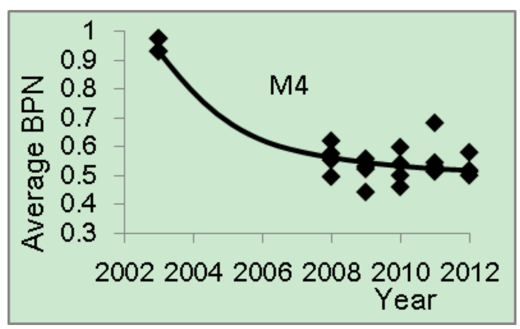
Average BPN—M1



Average BPN—M2



Average BPN—M3



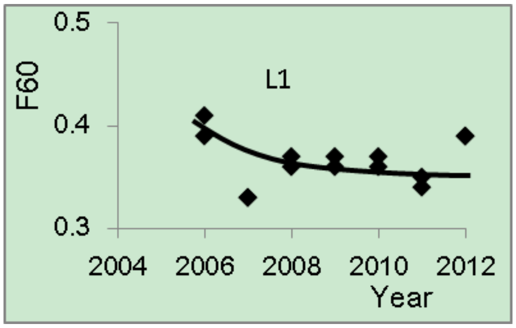
Average BPN—M4

Figure 4–6: A trend plot of average BPN with in-service years for six pavement sections.

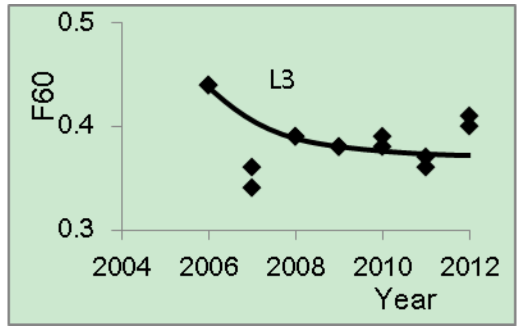
In addition, calculations were made for IFI in accordance with ASTM E 1960-03. IFI is a method used to calculate in common scale different measurements produced by different devices. IFI consists of two parameters: the speed constant predicted though the macrotexture measurements and harmonized friction at 60 km/hr, known as F(60). The calculated F(60) based on different measurement devices are summarized in Table 4–11. The trend plot of F(60) versus service time of pavement for the six pavement sections is shown in Figure 4–7.

Table 4–11: Computed F(60) values for different measurement devices for six pavement sections over the measurement period.

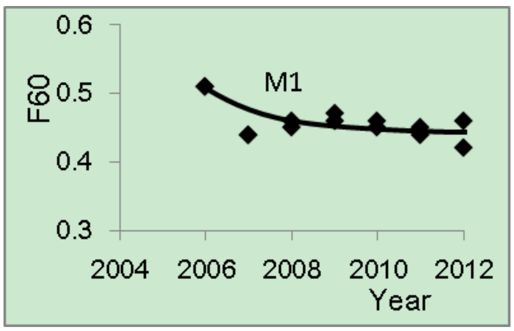
	Average of observed F60(LWST)							
	Direction	Year 0	2007	2008	2009	2010	2011	2012
Harrison R22 constructed at 2006 (L1)	E	0.41	0.33	0.37	0.37	0.37	0.35	0.39
	W	0.39	0.33	0.36	0.36	0.36	0.34	0.39
Harrison R250 constructed at 2006 (L3)	E	0.44	0.36	0.39	0.38	0.39	0.37	0.40
	W	0.44	0.34	0.39	0.38	0.38	0.36	0.41
Huron R162 Constructed at 2006 (M1)	E	0.51	0.44	0.45	0.46	0.45	0.44	0.42
	W	0.51	0.44	0.46	0.47	0.46	0.45	0.46
Huron 250 Constructed at 2000 (M2)	N	0.48	0.28	0.30	0.29	0.31	0.28	0.24
	S	0.46	0.26	0.28	0.23	0.24	0.31	0.21
Lucas R64 Constructed at 2004 (M3)	N	0.51	0.33	0.34	0.33	0.33	0.32	0.32
	S	0.51	0.33	0.34	0.35	0.36	0.33	0.35
Wood R25 – Drive Constructed at 2003 (M4)	N	0.48	0.33	0.38	0.35	0.33	0.34	0.34
	S	0.48	0.38	0.42	0.41	0.38	0.38	0.35
Wood R25 - Pass Constructed at 2003 (M4)	N	0.48	0.34	0.37	0.36	0.33	0.33	0.33
	S	0.48	0.39	0.43	0.42	0.39	0.34	0.37



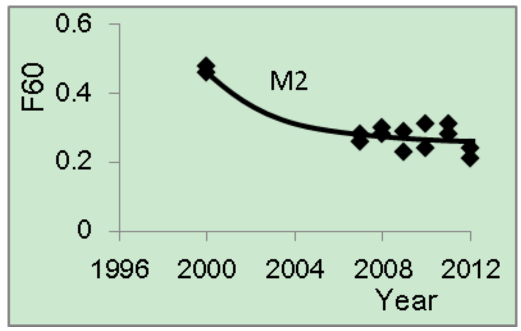
F60—L1



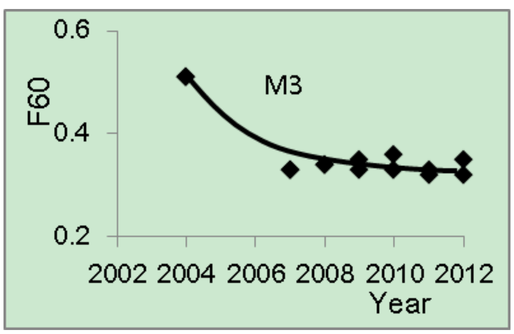
F60—L3



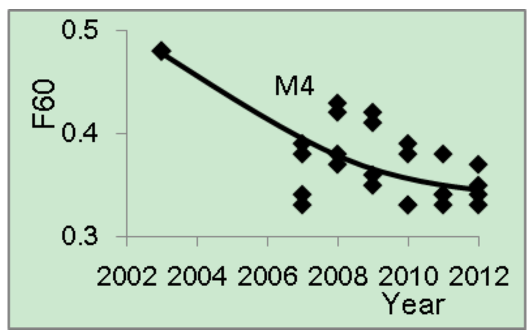
F60—M1



F60—M2



F60—M3



F60—M4

Figure 4–7: A trend plot of F(60) with in-service years for six pavement sections.

4.6. Concluding Remarks

In this chapter, field work pertaining to measurements of friction and texture properties at the selected six pavement sections for a duration of approximately 3 years was described. Data obtained were presented in Appendix D because of the large volume of information obtained. A condensed version of the measured data, namely, in terms of average value of each measurement type for each pavement section, was presented in this chapter. Trend plots of the condensed data were presented in figures to provide a visual observation of friction degradation behavior of in-service pavements. Based on the trend plots, important observations about the scattering and random nature of the measured data points could be made. According to trend plots, degradation of friction properties can be observed over a longer duration of in-service conditions. The measured friction data, in terms of SN(64)R and F(60) will be used in the following chapter to develop predictive models for in-service pavement friction degradations, taking into account the influences of site specific traffic data, aggregate gradation characteristics, and laboratory friction degradation curves obtained from the accelerated polisher presented in Chapter III.

5. PREDICTION MODELS FOR SKID RESISTANCE AND INTERNATIONAL FRICTION INDEX

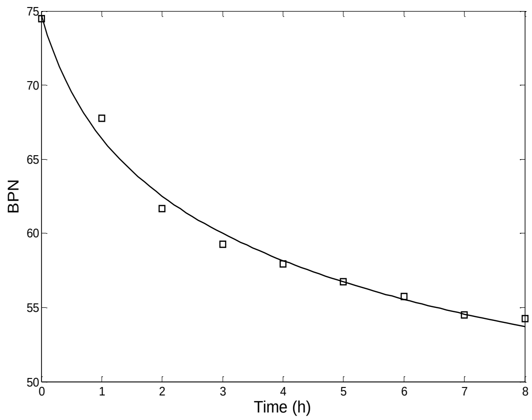
5.1. Introduction

This chapter presents the development of a predictive degradation model for SN(64)R for in-service asphalt pavement surface based on laboratory polishing test results using the commercial grade asphalt polishing machine, characteristics of aggregate gradation curve, and field traffic conditions represented by ADT. In addition, a predictive degradation model is developed for F(60) using the same set of predictors plus an additional predictor of the laboratory measured texture change (MTD) after an 8-hour polishing action. Validation of the developed prediction models are presented by comparisons between the predicted values with field measured values for the six pavement sections studied in this project.

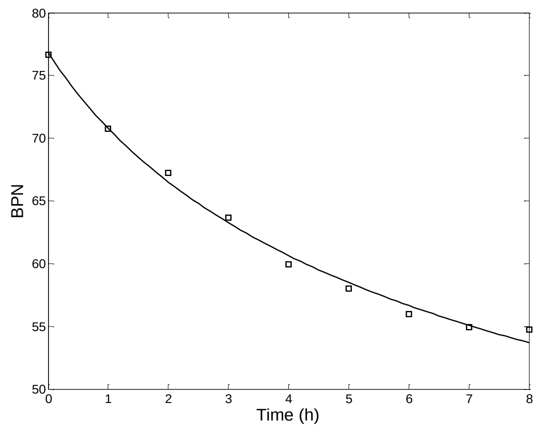
5.2. Developing the Predictive Degradation Model for SN(64)R

5.2.1. Model Formula and Parameter Analysis

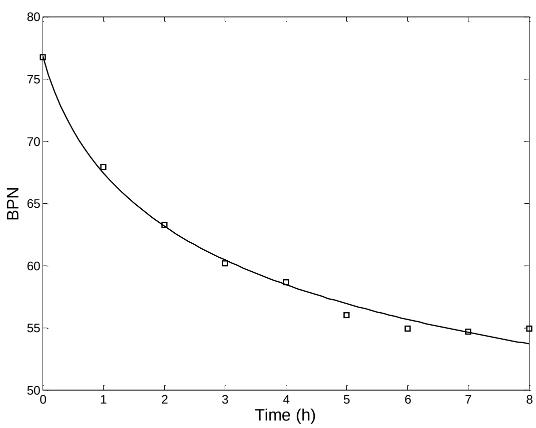
The first step in developing the degradation model for an in-service asphalt pavement surface is to examine the trend of friction degradation curves obtained from lab test results using an accelerated polishing machine. To this end, five friction degradation curves for five different mix designs with five different aggregate sources are reported in Figure 5–1 and are labeled as M1, M2, M3, M4, and L3, respectively.



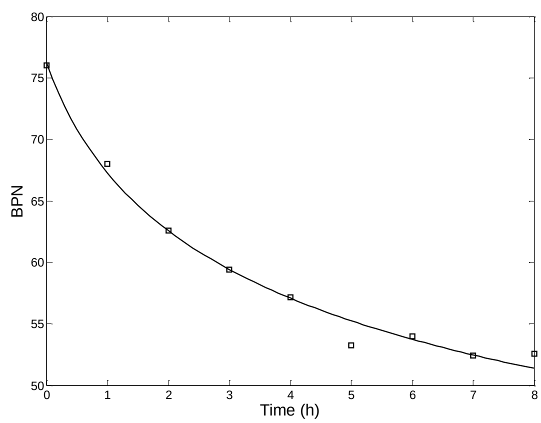
(a) BPN test of M1



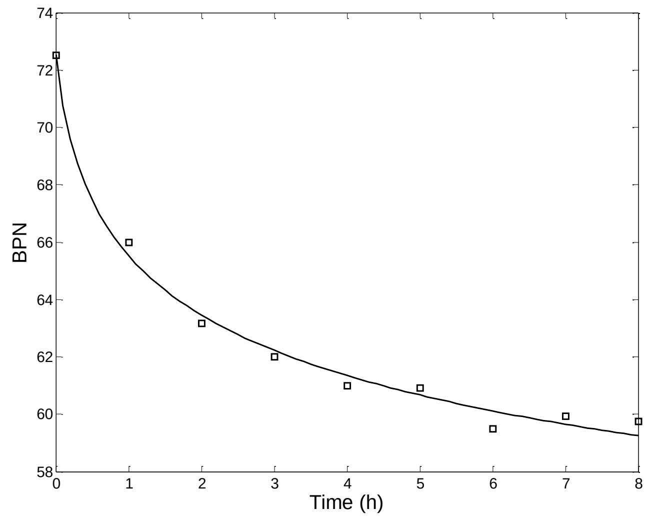
(b) BPN test of M2



(c) BPN test of M3



(d) BPN test of M4



(e) BPN test of L3

Figure 5–1: Lab test results for BPN values at different polishing durations.

Based on the trend curve of the plotted friction degradation curves, the convex power function was considered as the suitable mathematical form for curve fitting of the decaying trend. Thus, the time-dependent friction degradation curve can be expressed as Equation 5-1.

Model function:

$$BPN = BPN_0(1 + \frac{t}{t_0})^m \qquad (5\text{-}1)$$

where BPN_0 is the initial number of BPN, t_0 and m are two parameters to be referred to as “time index” and “scale index,” respectively. Assuming that this mathematical equation can be extended to describe the degradation of SN(64)R for an in-service asphalt pavement surface, then it is necessary to determine how the time index and scale index would affect the relationship between friction and time. A simple parameter sensitivity analysis is performed. First, the scale index *m* is fixed and a different time index t_0 is chosen; the parameter analysis result is shown in Fig 5–2(a). It demonstrates that the time index has the most effect on the time interval for reaching a stable friction value. It can be seen that the greater t_0 is, the longer the time duration required to reach a stable friction value. The scale index, *m*, plays a dominant role in affecting the value of friction at the residual state (or terminal state). As can be seen in Figure 5–2(b), the smaller the absolute value of *m*, the higher the residual friction value. From this simple parameter analysis, the proposed mathematical function for time-dependent friction decay seems quite suitable for its ability to provide a means to adjust both "time" and "friction value" scale.

The next step in model development is to consider the influencing factors of the in-service asphalt pavement surface that control the two scale parameters, namely time index and scale index. Based on a literature review of relevant research work (particularly the work performed for TxDOT) and judging the available field data in this research, four predictors (ADT, PV, κ, λ) and two responses (t_0 and *m*) are selected, as given in Equation 5-2 and 5-3. All the parameters are given in Table 5–1.

Time index: $t_0 = \alpha_1 ADT + \alpha_2 PV + \alpha_4 \kappa + \alpha_5 \lambda$ (5-2)

Scale index: $m = \beta_1 ADT + \beta_2 PV + \beta_4 \kappa + \beta_5\, \lambda$ (5-3)

$PV = \frac{BPN_o - BPN_8}{BPN_o} * 100$

where,

BPN_o = British pendulum friction number before polishing

BPN_8 = British pendulum friction number after 8 hours of polishing

Table 5–1: Predictors and responses for SN(64)R prediction model.

Predictors				**Responses**	
ADT	PV (%)	κ	λ	t_0	m

ADT: Average daily traffic.

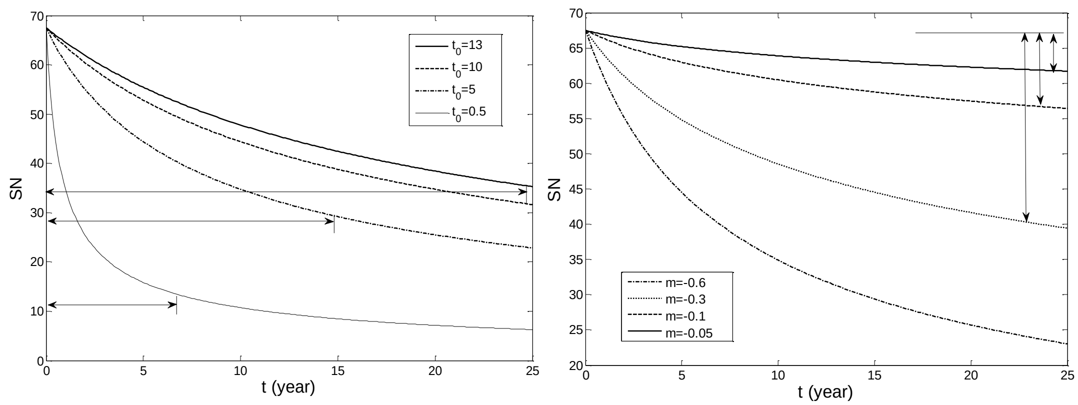
PV: Polishing value (see definition later).

λ: scale parameter of Gradation Curve.

κ: shape parameter of Gradation Curve.

Gradation Curve Fitting Equation: $Percentage\ passing = 1 - \exp(-(\frac{grain\ size}{\lambda})^{\kappa})$

t_0, m: calculated from the field data using regression method.



(a)m=0.6, choose different t_0 (b)t_0=5, choose different m

Figure 5–2: Parameter analysis of predictive model.

5.2.2. Determining the Model Coefficients

The model coefficients are determined using field measurement values of SN(64)R at different service years for the five pavement materials. The field data for determining model coefficients are taken from the materials labeled as M1 to M4 and L3. From nonlinear regression algorithm, the coefficients can be determined as follows:

Set **P** as the factor Matrix, which contains the information of highway traffic data (ADT) and the pavement material features, then the structure of the factor matrix is as follows:

$$P = \begin{array}{cc} \begin{matrix} \text{ADT} & \text{PV} & \kappa & \lambda \end{matrix} & \\ \begin{bmatrix} a_{11} & a_{12} & a_{14} & a_{15} \\ a_{21} & a_{22} & a_{24} & a_{25} \\ & \dots & & \\ a_{n1} & a_{n2} & a_{n4} & a_{n5} \end{bmatrix} & \begin{matrix} \text{Material 1} \\ \text{Material 2} \\ \\ \text{Material n} \end{matrix} \end{array} \qquad (5\text{-}4)$$

Once we have the factor matrix and the regression result of t_0 and m from field obtained friction degradation curves, a multiple regression analysis can be performed to determine the coefficient vectors of t_0 and m.

$$\alpha = P^{-1} * t_0 \qquad (5\text{-}5)$$

$$\beta = P^{-1} * m \qquad (5\text{-}6)$$

P^{-1} is the generalized inverse of factor matrix P and vectors α *and* β are model coefficients. Based on the available field data, the multiple regression result is given in Table 5–2.

Table 5–2: Multiple regression of model coefficients for SN(64)R prediction model.

Predictors	coeff_t_0 (**α**)	coeff_m (**β**)
ADT	-6E-4	-9.2196E-5
PV	0.287	0.0372
κ	-185.63	-2.3262
λ	1167.80	10.9279

Therefore, the friction degradation model for SN(64)R for the in-service asphalt pavement surface is as follows:

$$SN = SN_0(1 + \frac{t}{t_0})^m \quad (5\text{-}7)$$

Time index: $t_0 = -6.366 * 10^{-4}ADT + 0.2874PV - 185.632\kappa + 1167.8\lambda$

Scale index: $m = -9.2196 * 10^{-5}ADT + 0.0372PV - 2.3262\kappa + 10.9279\lambda$

SN_0 : Initial value of skid number. For new project, without field measured SN_0, The SN_0 could be determined by converting BPN_0 from the polishing test using equation (5-8) (Kissoff, N. V., 1988)

$$SN_0 = 0.862 * BPN_0 - 9.690 \quad (5\text{-}8)$$

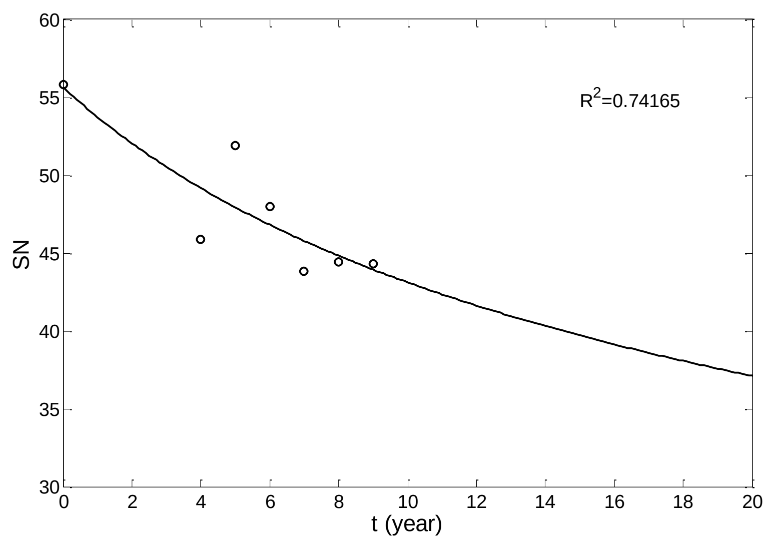
5.2.3. Prediction Results

In this section, the developed degradation model was used to predict SN(64)R for four pavement sections to facilitate comparisons with the measured data presented in Chapter IV. The basic required information for these four pavement sections are listed in Table 5–3.

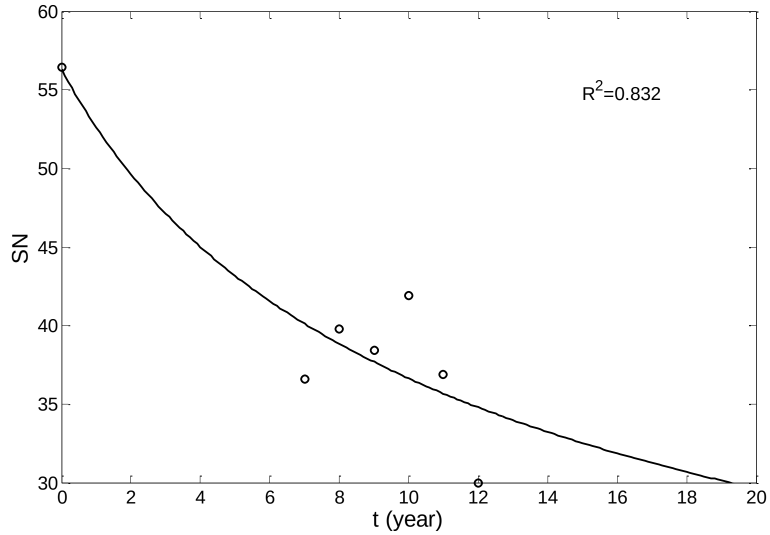
By substituting the predictors with the corresponding numbers in Table 5-3, the time index and scale index of each highway can be calculated (Table 5-3). Then, by plugging the indexes into the model Equation 5-7, the degradation of SN(64)R with in-service years can be predicted. The comparison of the predicted degradation curve with measured data is shown in Figure 5-3. It is noted that in Figure 5-3, SN_0 for each pavement section is calculated using equation (5-8). The quality of prediction is considered acceptable, considering the high R^2 value and the scattering of measured data. Using the mathematical function derived from the laboratory test results for field pavement may contribute to model errors.

Table 5–3: The predictor and response values for four highway sections.

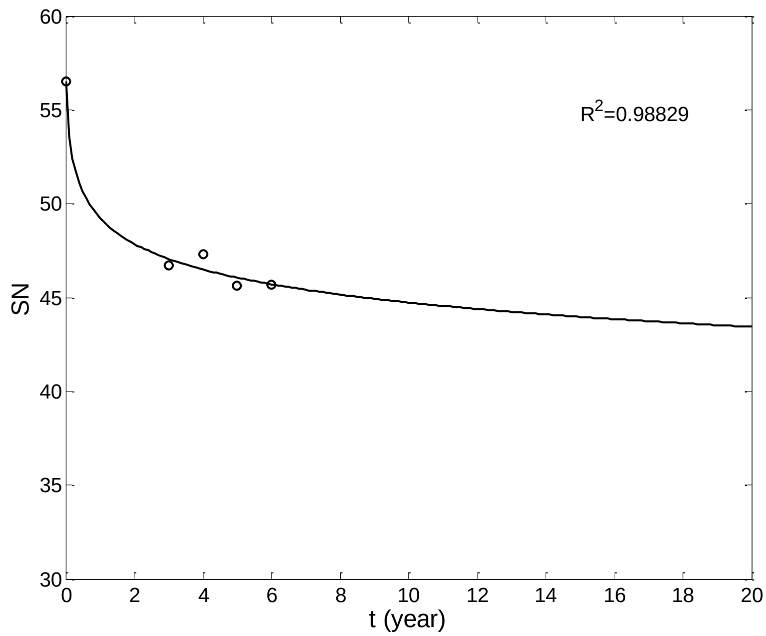
Highway	**Material**	**ADT**	**PV (%)**	**κ**	**λ**	t_0	**m**
Wood_drive	M4	11000	30.9	0.990772	0.164573	10.15	-0.37
Huron 250	M2	9290	28.6	1.150266	0.18598	5.97	-0.44
Lucas 64	M3	4390	28.4	1.092368	0.169079	0.041	-0.042
Harrison 250	L3	1430	17.6	1.086712	0.17634	8.35	-0.785



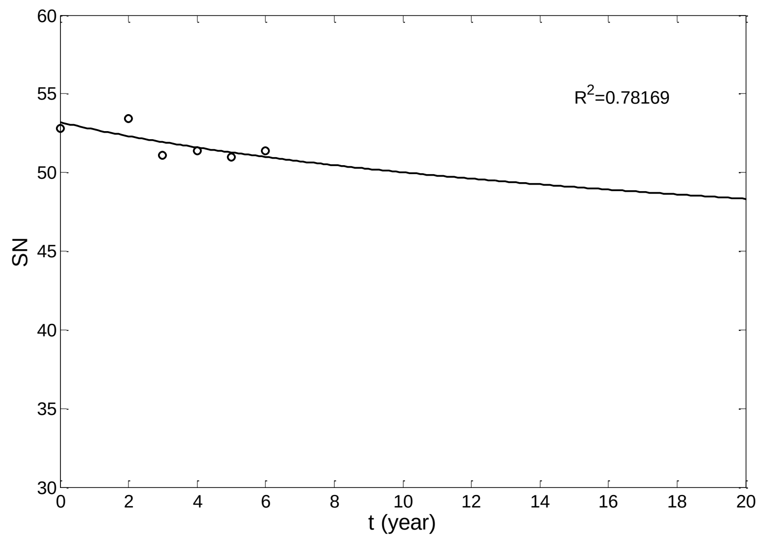
(a)Wood_drive M4



(b)Huron 250 M2



(d)Lucas 64 M3



(e)Harrison 250 L3

Figure 5–3: SN prediction curves for different pavement sections.

5.3. Developing the Predictive Model for F(60)

5.3.1. Model Formula and Coefficients

F60 is a harmonized friction value in the International Friction Index (IFI) by considering various friction measurement methods and influence of macrotexture measured by various devices. This would allow for a more standard approach to incorporate the previously identified dependence of friction on speed and texture. To develop a predictive degradation model for F60, an additional predictor of the texture degradation curve is needed.

Here, the mathematical function for degradation model of FT60 is the same as that used for SN. The procedure used to build up the prediction model of F60 is the same as the procedure described in the previous section for building the model for SN. The only difference is the number of the predictors adopted for predicting F60. To reflect the texture characteristic, we add two more predictor called texture value (TV) and t_stable. TV is calculated from lab test results according to the following equation.

$$TV = \frac{MTD_o - MTD_8}{MTD_o} * 100 \quad (5\text{-}8)$$

where,

MTD_o = Mean texture depth before polishing

MTD_8 = Mean texture depth after 8-hour polishing

And t_stable (hour) is the time lasted until the BPN is stable during the lab test.

Hence, this predictive model now has six predictors (ADT, PV, t_stable, TV, κ, λ) and two responses (t_0 and m). The definition of other predictors is provided earlier. These are shown in Table 5–4.

Table 5–4: Predictors and responses for F(60) prediction model.

Predictors						Responses	
ADT	PV (%)	t_stable (hour)	κ	TV (%)	λ	t_0	m

The multiple regression result, which is based on the available field data described in Chapter IV, is shown in Table 5–5.

Table 5–5: Multiple regression of model coefficients for F(60) prediction model.

Predictors	**coeff_t_0 (α)**	**coeff_m (β)**
ADT	0.000326255	-3.38E-05
PV (%)	0.115424394	-0.0123
t_stable	-1.11128602	0.035377
TV(%)	0.028789924	0.01938
κ	-12.00338736	-1.37305
λ	84.70763152	7.308794

Therefore the model for predicting F60 is as follows:

$$F60 = F60_0(1 + \frac{t}{t_0})^m \tag{5-9}$$

Time index: $t_0 = 3.26 * 10^{-4}ADT + 0.1154PV - 1.111t_{stable} + 0.0288\mathrm{TV} - 12\kappa + 84.71\lambda$

Scale index: $m = -3.38 * 10^{-5}ADT - 0.0123PV + 0.0354t_{stable} + 0.01938\mathrm{TV} - 1.373\kappa + 7.309\,\lambda$

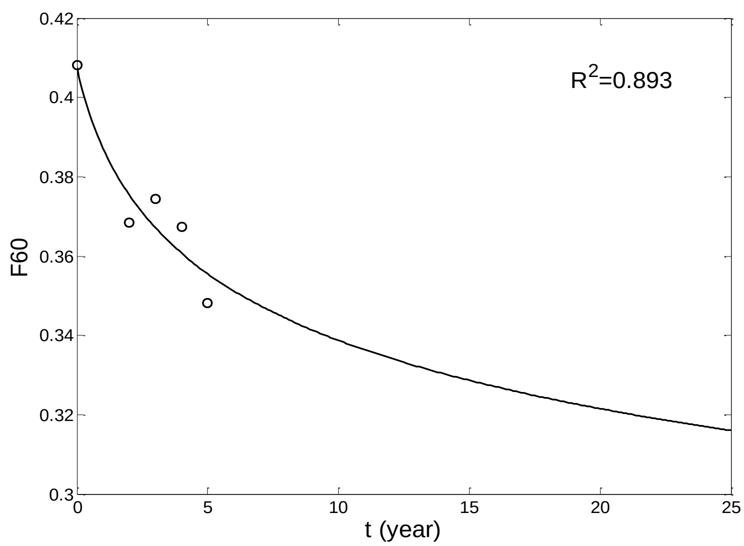
5.3.2. Prediction results

Six pavement sections with measured field data are used to test the prediction model. All the information regarding the predictors, as well as the calculated result of time index and scale index of F60 prediction function, is shown in Table 5–6

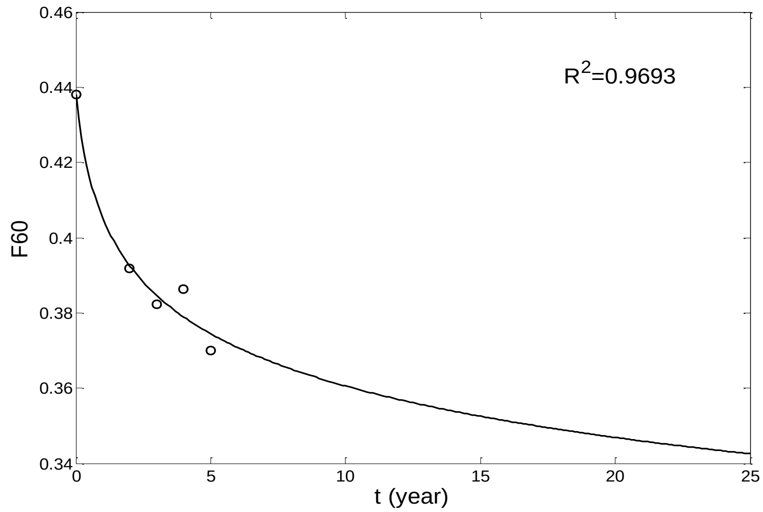
Table 5–6: The predictor and responses values for six highway sections.

Highway	**Material**	**ADT**	**PV (%)**	**t_stable**	**TV(%)**	**κ**	**λ**	**t_0**	**m**
Wood pass	M4	11000	30.9	5	26.08286	0.990772	0.164573	4.397891	-0.22692
Huron 162	M1	6000	27.2	7	25.54028	1.150266	0.18598	0.00018	-0.0148
Huron250	M2	9290	28.6	7	21.01167	1.150266	0.18598	1.104774	-0.23093
Lucas 64	M3	4390	28.4	6	25.96934	1.092368	0.169079	0.000436	-0.04627
Harrison250	L3	1430	17.6	4	13.9	1.086712	0.17634	0.346147	-0.05723
Harrison 22	L1	1300	19.6	4	8.977273	1.008409	0.174143	1.146686	-0.0814

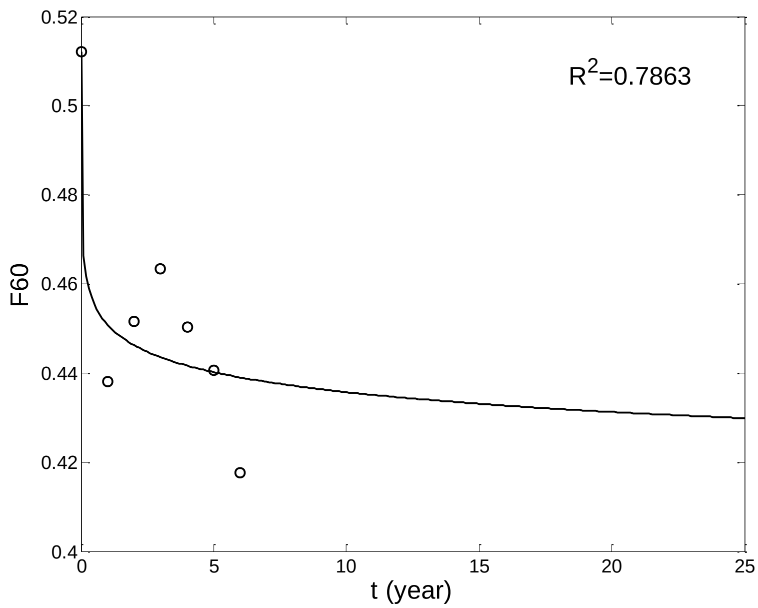
The comparison between the predicted and measured F60 is presented in Figure 5–4. The quality of prediction can be considered to be acceptable.



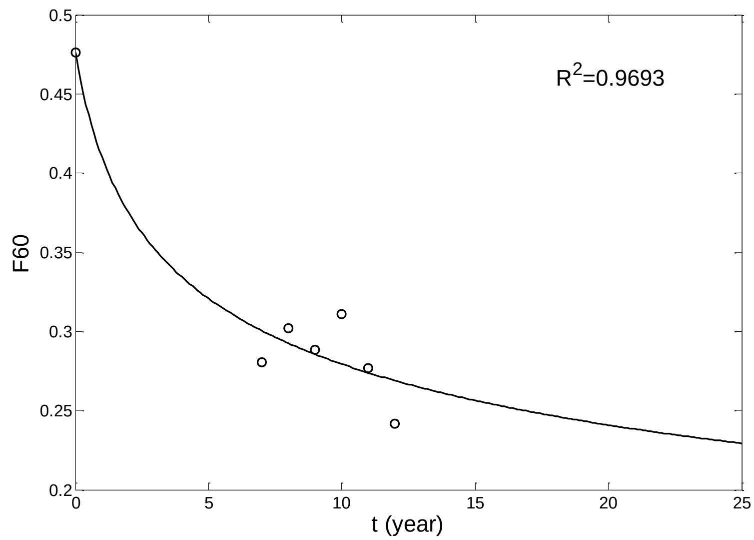
(a) Harrison 22L1



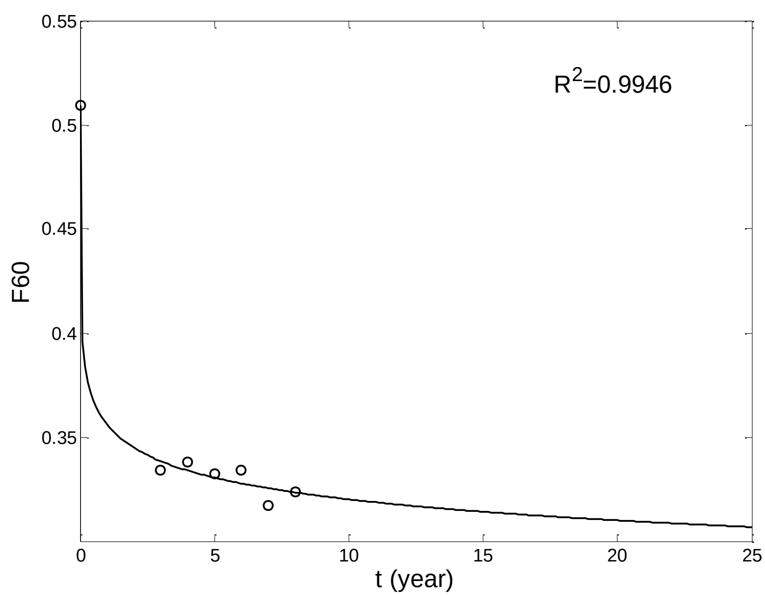
(b) Harrison 250L3



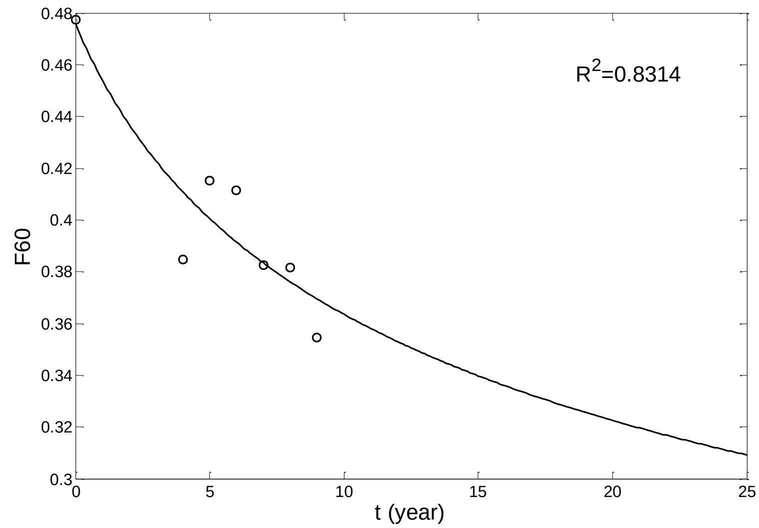
(c) Huron 162M1



(d) Huron 250M2



(e) Lucas 64M3



(f) Wood pass M4

Figure 5–4: F60 prediction curve of different pavement sections.

5.4 Summary

In this chapter, predictive degradation models for SN(64)R and F60 were successfully developed for in-service asphalt pavement surfaces. The predictors adopted for predicting SN(64)R consist of a laboratory friction degradation curve, traffic data, and aggregate gradation characteristics. The predictors for predicting F60 include one additional predictor of a laboratory measured MTD degradation curve. The mathematical function for the degradation models takes the form of a convex power function, which was based on observation of trend of laboratory polishing test result. Two indexes, time and scale, were the key parameters in the mathematical function to account for rate and magnitude of friction degradation. The accuracy and suitability of the developed prediction models are validated by comparisons with field measured friction data in six pavement sections with different construction materials, traffic condition, and in-service years. The developed prediction model is incorporated in the Supplemental Notes presented in Appendix E.

6. SUMMARY AND CONCLUSIONS

Preserving adequate friction and texture values during the entire life expectancy of asphalt pavement is of key importance to reduce skid-related accidents. The Ohio Department of Transportation (ODOT) has taken initiatives to ensure that pavement surfaces be monitored for skid number and that high accident pavement sections be replaced with high friction asphalt mixes. In this research, a commercial grade, laboratory-scale, accelerated polishing machine (the Polisher) has been developed and validated to test gyratory compacted HMA samples in order to obtain polishing and friction characteristics in a short test duration. Predictive friction degradation models for SN(64)R and F60 have been developed using the laboratory test data (friction degradation curve and texture degradation curve) from the Polisher, as well as traffic data and aggregate gradation curve parameters. Supplemental notes were developed for ODOT to implement the use of “The Polisher” for the purpose of evaluating the HMA samples of a JMF in providing adequate skid resistance throughout the design life of pavement sections.

6.1 Summary of Work Done

A review of relevant literature was conducted to ensure that the current research trend in the area of aggregate friction and polishing was critically evaluated. It is noted that this research has yielded many important findings and deliverables that are not available from other current research efforts. Most prominent among these is the development of a commercial grade asphalt polisher that provides an effective method to test gyratory compacted samples for quantifying the time-dependent polishing and friction behavior of HMA samples. In addition, friction degradation models for in-service asphalt pavement that were developed and validated in this research represent an integrated and comprehensive approach to forecasting the friction performance of HMA using lab test data, material characteristics, and field traffic information. Finally, a supplemental note was delivered to ODOT for consideration as a procedure for evaluating the suitability of a particular JMF and it's aggregate sources for a pavement project with consideration of project specific traffic data. The work performed under this research is summarized below.

- Field work was carried out to measure friction and texture data on six selected pavement sections for the years of 2010, 2011, and 2012. Additionally, coordination with ODOT personnel was made to obtain SN data using ODOT's locked wheel skid trailer. In 2012, additional friction and texture measurements were made on the shoulders of the selected pavement sections to serve as a surrogate for the initial friction and texture data.
- Analysis of field data was performed to see the trend of time-dependent variation in friction and texture for the six pavement sections. A general trend of degradation with increasing in-service years can be observed, even though there was significant scattering of data points.

- A new commercial grade accelerated polishing machine, The Polisher, was fabricated based on the findings and recommendations from the previously developed research-grade polishing machine documented in Liang (2009). The commercial grade polisher was designed to handle only standard gyratory compacted samples with a 6-inch diameter. The operation parameters such as vertical force, the rotational speed of polishing disc, and the rate of water flow onto the contact between the rubber disc and the sample, were fixed for simplicity and ease for maintenance. The comparison of test results between the research-grade machine and the commercial grade polisher confirms that the new polisher can reproduce the same result as the research grade machine. An operations manual for "The Polisher" was provided in Appendix A.
- Models for predicting the field performance of asphalt pavement friction under traffic were developed. The predictors for SN(64)R included the friction degradation curve obtained from the polisher, aggregate gradation curve characterization parameters, and traffic data. The predictors for F60 were the same as those for SN(64)R, but with one additional predictor of the MTD degradation curve. The developed prediction models were tested satisfactorily for accuracy for the six pavement sections studied in this research.
- Supplemental notes were developed for possible implementation by ODOT to evaluate the suitability of a particular JMF for a particular pavement construction project.

6.2 Conclusions

The conclusions from this study can be summarized as follows.

- The friction and texture data measured in the field for the six pavement sections showed significant scattering, even though efforts were made to conduct measurements at the same mile markers and same physical spots on the wheel path. The scattering can be attributed to high spatial variability as well as to uncertainties of environmental effects.
- The International Friction Index, by virtue of integrating friction and texture measurements and harmonizing differences in the measurement devices, appeared to be a useful index to represent friction and texture characteristics. As such, the use of IFI should be embraced by ODOT in future work.
- The functionalities of the new commercial grade accelerated polishing machine for gyratory compacted 6-inch-diameter samples have been validated. The design specifications of the machine were provided in the report. The use of “The Polisher” or other equivalent machines that satisfy the design requirements can be accepted in the lab for routine testing purposes.
- The prediction models for degradation of friction, either SN(64)R or F60, have been developed and compared with field measured data. It appeared that the predictive

equations could be used to forecast in service performance of asphalt pavement surface friction.

6.3 Recommendations for Implementation

The following recommendations are made for possible implementation:

- Adopt the developed commercial grade polishing machine, “the Polisher”, as an efficient laboratory test device to determine friction and polishing behavior of gyratory compacted HMA samples. Alternatively, the design specifications outlined in the report can be used to allow other interested commercial entities to fabricate equivalent accelerated polishing machines.
- The Supplemental Notes presented in Appendix E could be adopted by ODOT to evaluate the suitability of a JMF with a particular aggregate source for a specific pavement construction project.

6.4 Recommendations for Future Research

There are several research areas that ODOT could support to continue achieving ODOT’s mission of providing a safe pavement surface to minimize skid-related accidents.

- Systematically collect data on skid resistance and texture of interstate highway pavements for a long duration with the accompanied laboratory test program to characterize friction degradation curves and texture degradation curves using “the Polisher.” This will allow for a compilation of a statistically meaningful database for continuing to refine the methodology presented in this research.

- Initiate research to develop a procedure to adopt the use of the International Friction Index, F60, as a replacement to SN in reporting friction resistance of interstate highway pavements. Within this research, correlations between SN and F60 should be established, based on statistically meaningful data collected in the state of Ohio.
- The effects of the use of ribbed tires and smooth tires on the measured SN should be systematically evaluated from the Ohio specific database. In particular, additional study is needed to quantify the effects of microtexture and macrotexture on the friction properties of asphalt pavement surfaces.

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8. APPENDICES

APPENDIX A.

OPERATION MANUAL

FOR

THE POLISHER

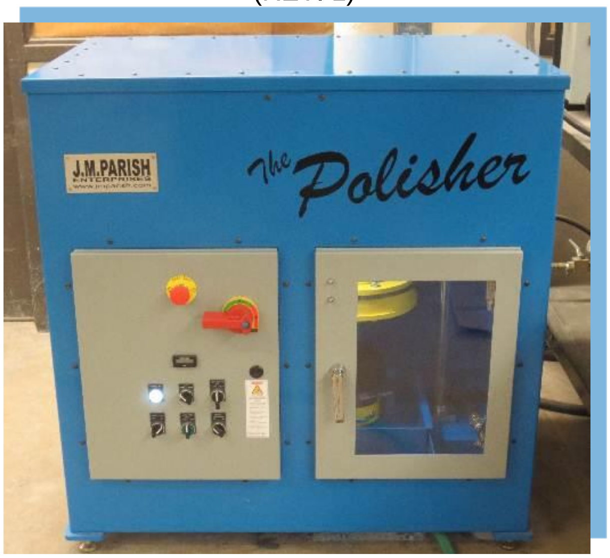
J.M.PARISH ENTERPRISES, LLC

J.M. Parish Enterprises
95 16th Street
Barberton, OH 44203

OPERATION MANUAL
FOR
THE POLISHER

Machine Part No. D68-12-004
Serial No. 0001
JMP Report No. 68-12-004

January 14, 2013
(REV. 1)



PREPARED BY: ______________________________________
L.J. PETIT

APPROVED BY: ______________________________________
J.M. PARISH

PROPRIETARY DATA NOTICE

REVISIONS

Rev.	Description of Change	Approved By	Date
1	Initial Release	JMP	01/14/13

TABLE OF CONTENTS

1.0 SCOPE

The Polisher prepares or polishes the surface of fresh asphalt samples in a controlled process. The polished samples may be tested for traction, wear, or other properties. The consistency of the polish process is critical when comparing data with other samples or correlating data for estimating life.

The processes are critical in determining how different aggregates affect durability, traction, and wear over time.

This manual discusses The Polisher, focusing on safety, installation, components, procedures, services, and other items associated with The Polisher

It is strongly recommend that The Polisher operator reads and understands this manual for proper safety and use.

2.0 SAFETY

The Polisher is an automatic machine; once items on the checklist are completed and the operation starts, the operator need not take any action until the cycle is complete.

The items on the operation check list should be observed for safety precautions. Refer to operation check list in appendix b.

As with any testing equipment, caution must be taken at all times.

Respect for equipment, good judgment, and constant observation of the work area are a must.

Internal company procedures must be established for safety and operation.

Contact J.M. Parish Enterprises for all questions or concerns.

WARNING: FAILURE TO FOLLOW THESE RULES MAY RESULT IN PERSONAL INJURY

1. **FOR YOUR OWN SAFETY, READ INSTRUCTION MANUAL BEFORE OPERATING THE POLISHER.** Learn the machine's applications and limitations and understand that hazards may arise.
2. **ALWAYS KEEP PANELS INSTALLED.**
3. **NEVER REMOVE ANY SAFETY LOCKS.**
4. **ALWAYS WEAR EYE PROTECTION.**
5. **MAKE SURE ALL TOOLS AND OTHER ITEMS ARE CLEAR OF MACHINE** before starting up machine.
6. **DON'T USE IN DANGEROUS ENVIRONMENT**. Always keep machines in a dry, clean work place.
7. **KEEP WATER AWAY FROM ELECTRICAL COMPONENTS**.
8. **ONLY ALLOW AUTHORIZED PERSONNEL TO OPERATE MACHINE.**
9. **ALWAYS USE PROPER TOOLS, CLOTHING, AND PRECAUTIONS.**
10. **ALWAYS SHUT OFF ALL POWER TO THE POLISHER BEFORE PERFORMING MAINTENANCE OR CLEANING.**
11. **ALWAYS MAINTAIN TOOLS AND MACHINES**. Keep tools and machinery clean and lubricated properly.
12. **NEVER STAND ON THE POLISHER**, it is not a proper place to stand or store any objects on the machine.
13. **DISCONTINUE USE IF A PART IS DAMAGED,** call JM Parish Enterprises for spare or replacement parts.

14. **BE SURE TO UNDERSTAND PROPERTIES OF MATERIALS.** Certain samples may contain chemicals or have properties that are harmful, use all necessary precautions.
15. **PROPERLY DISPOSE OF WASTE AND DEBRIS CREATED BY THE POLISHER.**
16. **DO NOT RUN MACHINE IF UNDER THE INFLUENCE OF DRUGS, ALCOHOL, OR ANY OTHER MEDICATION.**

3.0 PART NUMBER AND SERIAL NUMBER

Each Polisher includes a part number and serial number. These may be found on the ID tag on the access door frame.

Each machine is designed for specific requirements. The part number and serial number should be recorded and are essential for tracking historical data and for providing proper service.

4.0 INSTALLATION

Upon receiving The Polisher, inspect crate for any damage done during shipping. If damaged, take note. The Polisher should be installed in a good, clean environment on a level surface. It should be placed at a location where it is not likely to be struck by heavy (or otherwise harmful) objects. Damage to The Polisher may result in inaccurate. It should be placed in a secluded or lab type location. Only trained personnel should have access. J.M. Parish Enterprises does not take responsibility for stolen, damaged, or otherwise altered machines. J.M. Parish Enterprises is not responsible for the installation or placing of The Polisher.

5.0 POWER

Each Polisher is sized for specific power arrangements. The part number and serial number may be used to track the power requirements for each machine. Power requirements appear on the label inside the control box and are in this manual. Only certified electricians familiar with the national and local electrical code standards may wire this machine.

This machine must not be altered in any way. Schematics and the bill of materials for electrical components are in appendix a.

6.0 EQUIPMENT

This section pictures basic components and indicates their general functions. Further descriptions of items and their functions are provided later in this manual. This section should be referred to if any questions arise about components or their basic functions.

Over View
Figure 6.1

6.1 Over View – Figure 6.1

1: **The Polisher.** Front view of The Polisher.

2: **Control Box/Control Panel.** An emergency shut off button is located for quick shut off. To reset, pull emergency shut off button outward until it clicks. The breaker switch turns electricity on and off to The Polisher. Switch to appropriate position. See Section 6.5 for control buttons.

WARNING: THERE ARE MOVING PARTS INSIDE THE POLISHER

3: **Access Door.** The access door provides protection to the operator from moving parts. A clear window allows for the operator to view the sample as it is being polished. A safety lock is located inside on the door frame which prevents the machine from operating unless this door is closed. To open the access door, turn the handle clockwise 90 degrees and pull. A lock mechanism is included in the handle so the operator can install a pad lock if desirable.

The Polishing Chamber
Figure 6.2

6.2 The Polishing Chamber – Figure 6.2

1: **The Polishing Chamber.** The polishing chamber is where polishing occurs, and can be accessed through the access door.

2: **Sample Tray.** The removable tray collects water and debris from polishing. Four pins on the bottom keep it in place so that it is always in the correct position. A water drain is located in the front. The sample bracket holds the sample piece in the correct position. The sample tray can be easily removed and washed out. A drain hose is connected to the bottom of the try via a quick disconnect fitting. To remove the tray, release the quick disconnect hose coupling and lift until pins disengage.

3: **Particle Trap.** The particle trap stops debris from going into the drain. Debris will fall to the bottom of the tray. Water flows under or over the particle trap into the drain. The particle trap can be removed by lifting. It is registered in place by two pins.

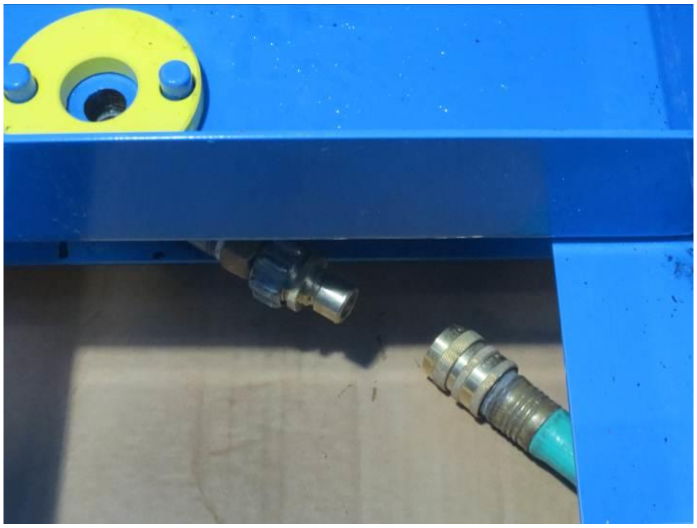
4: **T-Bolt Band Clamp.** This clamp holds the sample in place for polishing. It can be unclamped but pushing in the safety lock and pulling the latch outward; loosening it so that the sample may be installed or removed. The ends of the clamp can be separated by disengaging the t-bolt with clip. See procedures in Section 8.4 for clamping samples.

5: **Sample.** A 6" diameter by 4" high cylindrical sample of asphalt is shown. It is held in place by the t-bolt band clamp. The Polisher is designed to hold and polish a 6" diameter by effective 6" high sample. A 6" diameter by 4" high sample may be polished if the spacer is used. See Section 8.4 for sample installations.

6: **Water Supply and Shut Off Valve.** A service water line must be connected to The Polisher. A 1/4 NPT fitting and regulator is supplied with the machine. The regulator must be adjusted for low flow into the machine. See water section 7.0.

7: **Shaft Assembly.** The shaft assembly includes the mounting plate that supports the polish disc. Other than changing the polish disc, the shaft assembly should not be tampered with.

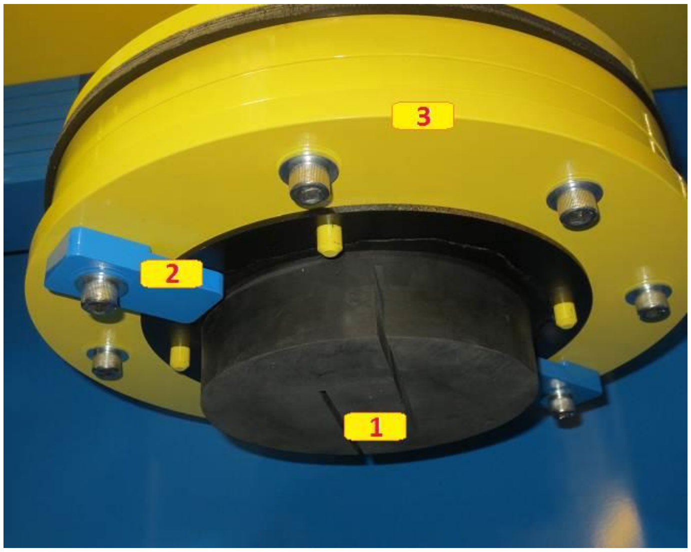
8: **Water Drain.** The water drain is attached to the bottom of the sample tray.



Drain Line Quick Disconnect – Disconnected
Figure 6.2.1

Drain Line Quick Disconnect - Coupled
Figure 6.2.2

9: **Quick Disconnect Coupling.** The Polisher includes 1/2 fittings and a hose quick disconnect coupling. The drain line may be a temporary hose or a fixed pipe. The drain line quick disconnect coupling must be disconnected to remove the tray. Refer to Figures 6.2.1 and 6.2.2.



Polish Disc
Figure 6.3

6.3 Polish Disc – Figure 6.3

1: **Polish Disc.** The rubber polish disc polishes the asphalt surface on the top surface of the sample. Two slots allow water to flow through and lubricate the sample. This item **is designed to wear out** (typically after four hours of use) and will need replaced. Contact J.M. Parish Enterprises to purchase new polish discs. The polish disc is registered by four pins attached to the shaft assembly mounting plate and is secured with two swivel locks.

CAUTION: USING SUBSTITUTE POLISH DISCS WILL RESULT IN INACCURATE RESULTS.

2: Swivel Locks. Two swivel locks hold the polish disc on to the shaft mounting plate. See installment process in Section 8.5.

3: Mounting Plate. The mounting plate includes the four register pins for the polish disc, and provides the surface for the disc to bear against.

The Water Flow Meter
Figure 6.4

6.4 Water Flow Meter - Figure 6.4

1: **Water Flow Meter.** The water flow is critical to obtain consistent results. Rotate the adjustment knob to adjust the flow. Water flows through the shaft assembly and polish disc. See water Section 7.0.

2: **Adjustment knob.** This knob is for making small adjustments to the flow. Rotate clockwise or counter-clockwise to obtain approximate 100 cc/min flow.

Control Box/Control Panel
Figure 6.5

6.5 Control Box/Control Panel - Figure 6.5

1: **Timer.** The timer indicates hours of operation for the period under test, and continues timing machine operation until it is reset. It may be used to track sample polishing time.

2: **Power On Light.** This is an indicator light. If it is lit up, power is available and the machine may be operated.

3: **Work Light.** This switch turns the work light on or off to view the sample being polished through the access door. The light does not need to be on or off during polishing, it is for convenience only. The light is located inside the machine.

4: **Hand/Off/Auto Switch.** This switch allows the operator three options; hand, off, or auto. Hand is a manual mode for The Polisher. When in hand mode, switches 5 and 6 can be used. The auto position puts the machine in an automatic mode. This activates the auto mode reset/hold/run switch. This is the key mode for polishing. The off position of the switch disables both hand and auto. For more information on the different modes, see the procedures Section 8.0.

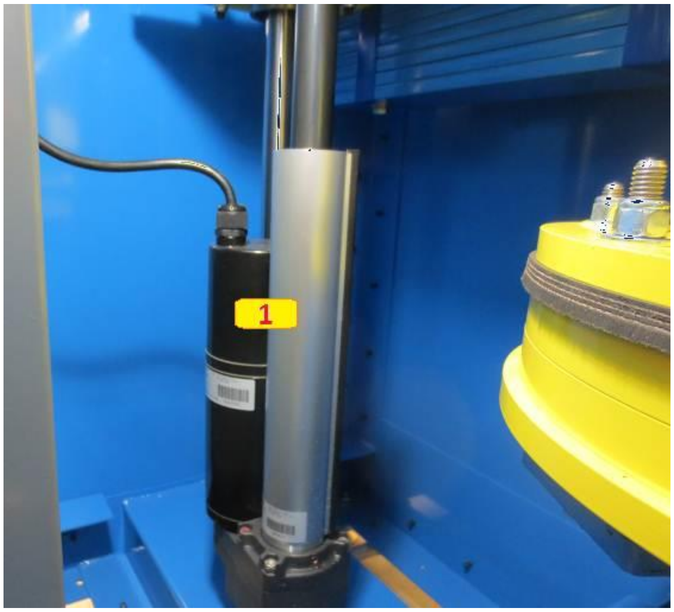
5: **Manual Actuator: Load/Unload.** When the hand/off/auto switch is in hand, the manual actuator: load/unload switch may be used. This switch allows the operator to load or unload the shaft. Load will move the shaft assembly/polish disc downward, unload will move the shaft assembly/polish disc upward. This switch is spring loaded, when released it will return to the off position so that the operator cannot leave machine while the main actuator switch is activated. The shaft assembly and polish disc remains in the position the operator left them in.

6: **Manual Rotation Switch.** When the hand/off/auto switch is in hand, the manual rotation switch may be used. This switch allows the operator to rotate the shaft assembly/polish disc. The manual switch can be in the on or off position. It is spring loaded, so when not activated, the switch will revert back to the off position, thus stopping rotation.

7: **Auto Mode Switch.** When the hand/off/auto switch is in auto, the auto mode switch is activated. This switch can be set to reset, hold, or run. The reset setting will reset the automatic mode. Hold will stop the polishing process, and the shaft assembly will stop and rise. The sample can be inspected through the access door window. Run will allow the automatic mode to progress.

Note: If the door is opened, the E-STOP hit, or the auto mode is switched to reset, the 1 hour timed run period is reset. Thus, once polishing begins, the machine will run for 1 hour period.

8: **Control Panel Lock.** This lock is to prevent easy access to control box by unqualified personnel.



Actuator
Figure 6.6

6.6 Actuator – Figure 6.6

1: **Actuator.** The actuator raises and lowers the shaft assembly. This should not be tampered with.

Lock Out Receptor
Figure 6.7

6.7 Lock Out Receptor – Figure 6.7

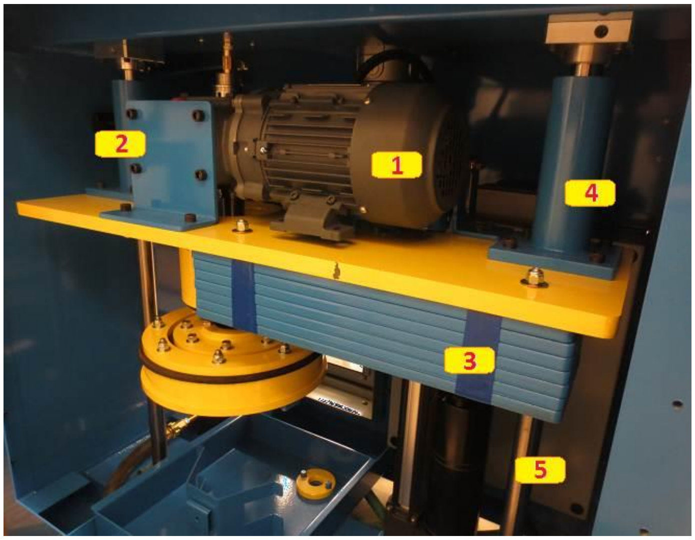
1: **Lock Out Receptor.** The access door lock out receptor is in the upper left of the access door.

The machine will not operate without the door being closed and the key engaged in the receptor.

Lock Out Key
Figure 6.8

6.8 Lock Out Key – Figure 6.8

1: **Lock Out Key.** The access door lock out key is located on the upper corner of the access door, and positioned to be inserted into the receptor at the proper depth with the door closed. The machine will not operate without the door being closed and the key engaged in the receptor.



Mechanical Equipment (Back Panel Removed)
Figure 6.9

6.9 Mechanical Equipment – Figure 6.9

1: **Motor.** The motor drives the shaft assembly, thus rotating the polish disc on the shaft. The speed on the motor and shaft is constant, no adjustment is needed.

2: **Gear Box.** The constant speed motor is reduced by the constant gear reducer. No Adjustment is required.

3: **Weights.** The weights produce constant gravity, which maintains polish force. The weights must be maintained as factory set. No additional weight should be added, nor should any weight be reduced; or polish results will vary.

4: **Linear Bearing Housing.** The linear bearing mechanism hold the shaft assembly so the polish disc is positioned correctly over sample.

5: **Linear Shaft.** The linear bearings in the housing rides along the linear shaft.

Light
Figure 6.10

6.10 Light – Figure 6.10

1: **Light.** The light as it is installed at the top of the inside of The Polisher. It is directly behind the control box. The line and protective frame must be kept in place for safety. When the bulb must be replaced, unscrew the frame and bulb.

7.0 <u>WATER</u>

Water is critical for polishing; polishing will not occur without it. Water lubricates the asphalt sample and allows the rubber to wear, creating a polished surface on the sample. Without water, the asphalt and rubber will grind down, resulting in a rough, uneven surface. Once the rubber is worn, the polish disc will no longer polish effectively.

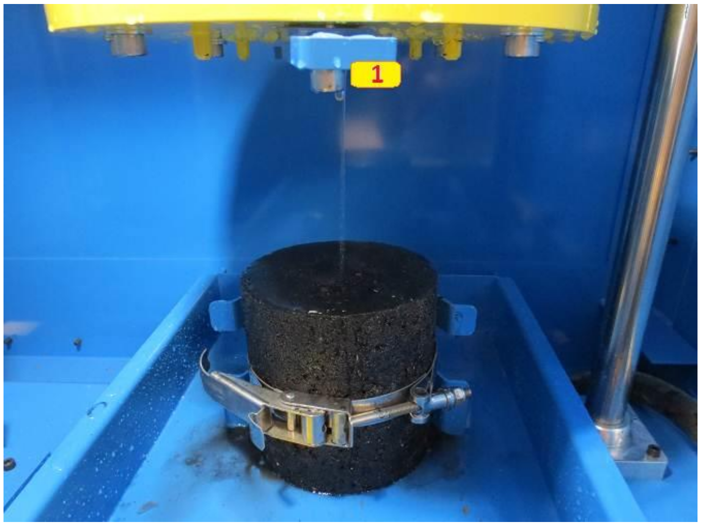
Prior to running a sample, inspect a consistent flow through the polish disc.

Water Inlet Valve and Regulator
Figure 7.1

7.1 Water Inlet Valve and Regulator – Figure 7.1

1: **Water Line Valve.** The water line valve is used to shut off or turn on water to The Polisher.

2: **Regulator.** The regulator adjusts flow into The Polisher. Typically, the regulator is set by installment. The manufacturer suggests turning the regulator knob counter-clockwise just until knob stops before turning on the system. Then, turn pull knob upward to unlock. Turn regulator clockwise until pressure is around the 100 mark on the flow-meter. When changing a pressure setting, always begin at a lower pressure and work your way up. To lock the pressure setting, push knob inward.



Inspect Water Flow Over the Sample
Figure 7.2

7.2 Inspect Water Flow Over Sample – Figure 7.2

1: **Water flow.** It is important to have proper water flow onto the sample. Always inspect water flow after installing the polish disc and sample before running any cycles.

8.0 PROCEDURES

This section is to describe various procedures that an operator will most likely have to perform in order to use The Polisher.

An operation check list is located in appendix b. It provides general guidelines for typical operation.

8.1 Power On

Once confirming the polish chamber is clear and the sample is ready to be polished, The Polisher can be turned on. Pull the E-STOP button out. Switch the breaker switch to the on position. Select which mode you wish to work in (manual or automatic).

8.2 Manual Mode

The manual mode is to ensure a proper set up, not for extended polishing. The sample must be positioned and clamped in place prior to using the manual mode features. Manual mode is used to manually load or unload the sample and/or start or stop rotation. When in manual mode, the hand/off/auto switch must be turned to hand. Manual mode enables the manual actuator load/unload and the manual rotation off/on switch

8.3 Automatic Mode/Polishing a Sample

Automatic mode is used for polishing a sample for a one hour period. To enable automatic mode, turn the hand/off/auto switch to auto. When in automatic mode, the auto mode switch is enabled, and the manual actuator and manual rotation switches are disabled. To start polishing, the operator must confirm 100 cc/min water is flowing over the sample, and have a sample and proper polish disc correctly installed (see procedure Sections 8.4 and 8.5 for more information). Next, the operator must be sure that the access door is closed. The operator may then switch the auto mode switch to run. There will be a seven second delay, and then the machine will datum, or return to the starting position, moving the shaft completely up. Rotation will then begin, and the shaft will lower onto sample. During automatic polishing, polishing will continue for one hour. The Polisher will stop and return to the datum position. At any time during polishing, the sample can be inspected by turning the auto mode switch to hold. The shaft assembly will return to the datum position. The sample may be viewed through the access door window. After inspection, the auto mode switch can be turned to run to continue the one hour polish cycle. It is not necessary to have the work light on during polishing, and can be turned on or off accordingly. If at any time, the polishing is interrupted, the timer will not reset unless instructed to.

Note: If the automatic mode is interrupted, the access door opened, power is lost, the E-STOP is pressed, or the auto mode switch is turned to rest, the one hour polish time will reset.

8.4 Installing Samples

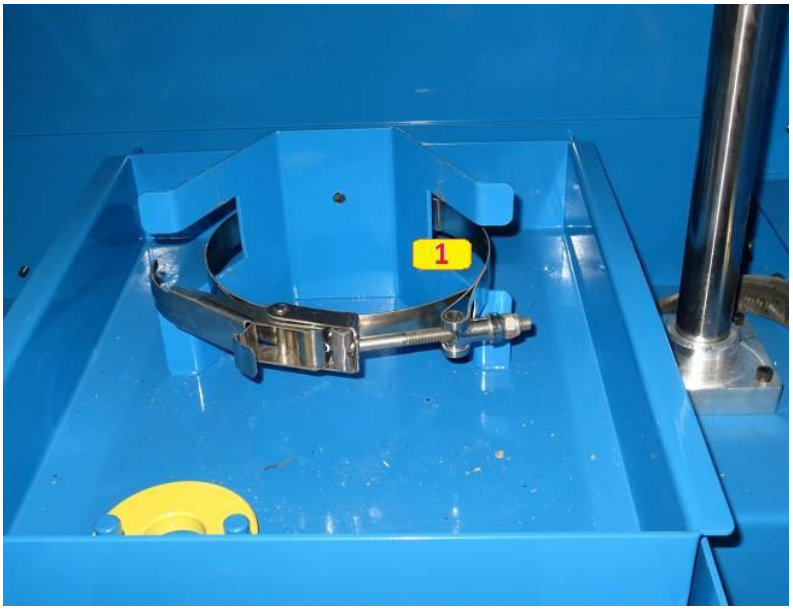
Typical Asphalt Sample
Figure 8.4.1

8.4.1 Typical Asphalt Sample – Figure 8.4.1

1: **Asphalt Sample.** A typical 6” diameter by 6” high is shown

Typical samples are either 6” diameter by 6” high or 6” diameter by 4” high. If using a 4” high sample, **the spacer must be used** to locate the sample at the correct height.

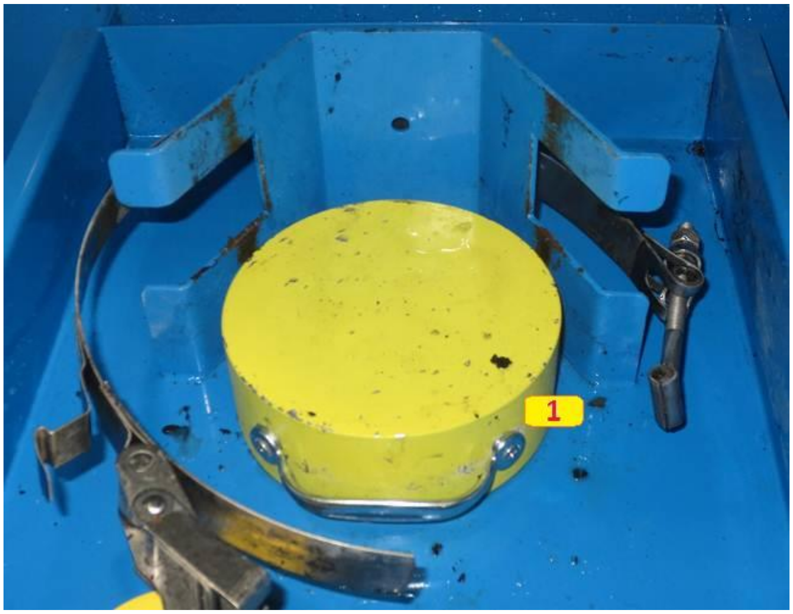
Before installation, make sure the tray surface inside the bracket (where the sample will go) and the bracket itself are clean of any debris. Any factors making the sample un-level will cause uneven results. Once the tray and bracket are clean and the surface is confirmed to be level, the operator can then install a sample. Tighten the t-bolt clamp by pushing clamp inward until safety clicks through the clamp. It is important to make sure the safety clicks so that the clamp will not loosen during polishing.



Sample Tray with No Sample
Figure 8.4.2

8.4.2 Sample Tray with No Sample – Figure 8.4.2

1: **Sample Bracket.** Whether installing a 6” diameter by 6” high sample or a 6” diameter by 4” high sample, the operator must start with a clean sample tray.



Installing the Spacer
Figure 8.4.3

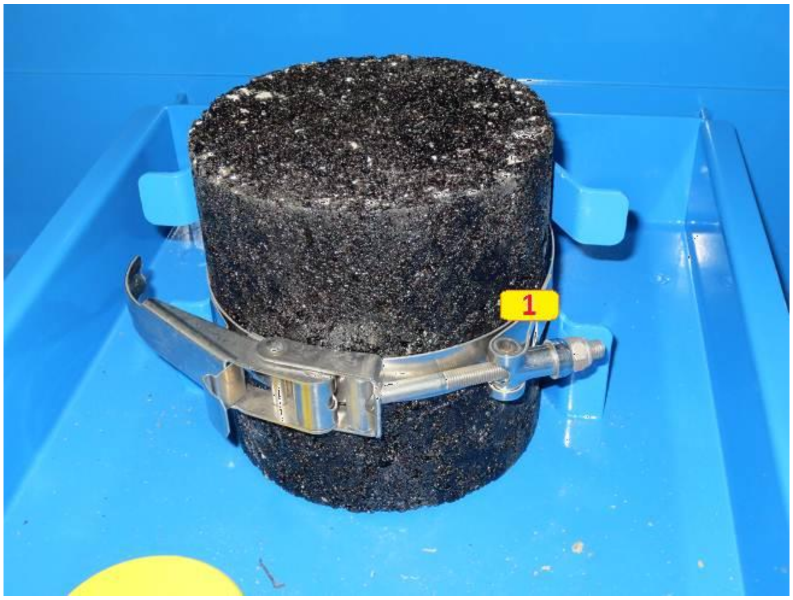
8.4.3 Installing the Spacer (if Applicable) – Figure 8.4.3

1: **Spacer.** The spacer is required when polishing a 6” diameter by 4” high sample. To install the spacer, first make sure there are no debris or other objects in the sample tray that would keep the spacer from being level. Then grasp the spacer by the handle and place it in the middle of the sample bracket and slide it back until the rubber bumpers engage the bracket.

6"X4" Sample Installed
Figure 8.4.4

8.4.4 6" Diameter by 4" High Sample Installed – Figure 8.4.4

1: **6" X 4" Sample Installed.** Place the sample on top of the spacer and tighten the T-bolt clamp so that the sample is secured. Make sure sample is level. Notice the safety is through the clamp. Also, notice how the clamp wraps around the sample securing it so that it may not move. The bracket and t-bolt are designed to hold the sample firmly in place for polishing.



6"X6" Sample Installed
Figure 8.4.5

8.4.5 6" Diameter by 6" High Sample Installed – Figure 8.4.5

1: **6" X 6" Sample Installed.** The 6" diameter by 6" high sample does not need to the spacer. Make sure there are no debris or other objects on the sample tray that would keep the sample from being level. If the tray is clear of any objects, place the sample in the middle and secure with the T-bolt. Notice the safety is through the clamp. Also, notice how the clamp wraps around the sample securing it so that it may not move. The bracket and t-bolt are designed to hold the sample firmly in place for polishing.

Pressing the Clamp Safety Button
Figure 8.4.6

8.4.6 Clamp Safety Button – Figure 8.4.6

1: **Safety Button.** To undo the clamp, press in the safety button and pull the latch to loosen the t-bolt clamp. Then the sample should be able to be easily removed.

8.5 Installing Polish Disc

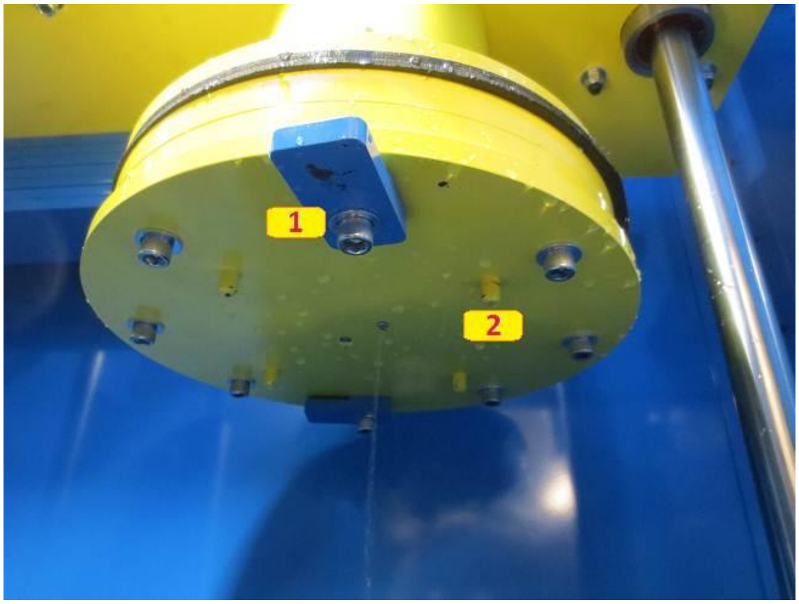
Typical Polish Discs
Figure 8.5.1

8.5.1 Typical Polish Discs – Figure 8.5.1

1: **Polish Discs.** The polish discs are specially designed for The Polisher.

Using new polish discs or polish discs with evenly worn surfaces is critical to obtaining a properly polished sample. A polish disc typically lasts four hours, so the polish disc must be changed accordingly so. Polish discs can be purchased from J.M. Parish Enterprises at any time.

Have multiple polish discs in reserve, so tests are not held up due to lack of the proper materials.

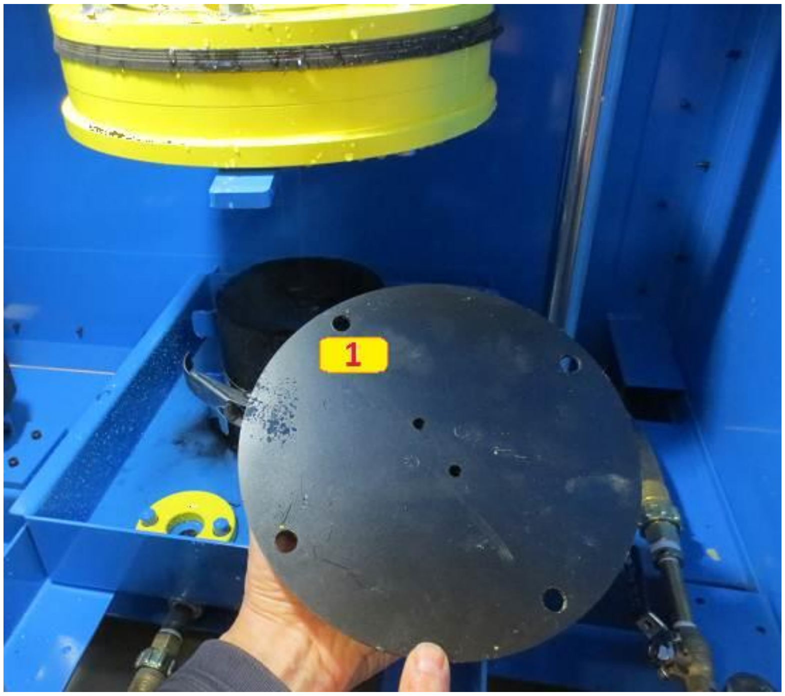


Mounting Plate without Polish Disc
Figure 8.5.2

8.5.2 Mounting Plate without Polish Disc – Figure 8.5.2

1: **Swivel Lock.** The swivel lock is used to hold the polish disc to the mounting plate. A hand knob is located on top to allow for loosening the swivel lock easily. Typically, tools are not required to install or change polish discs.

2: **Register Pins.** Four register pins are located on the mounting plate to align with four holes in the polish disc.



Polish Disc Pin Holes
Figure 8.5.3

8.5.3 Polish Disc Pin Holes – Figure 8.5.3

1: **Pin Holes.** There are four pin holes located around the polish disc that match with the register pins in the mounting plate.

Align the pins in the mounting plate with pin holes in polish disc. Raise the polish disc in place. The water flow holes on the disc will match the holes on the shaft mounting plate when the disc is installed. Rotate swivel lock to hold the polish disc in place to free hands for tightening.

Hand Knob for Swivel Lock
Figure 8.5.4

8.5.4 Hand Knob for Swivel Lock – Figure 8.5.4

1: **Hand Knob.** Two hand knobs are located on the shaft assembly for easy tightening/loosening of the swivel locks.

With the polish disc being held in place by swivel locks, tighten the hand knob while holding the swivel lock in place. The screw does not need to be extremely tight. Tighten the other swivel lock the same way.

8.6 Inspecting Alignment of the Sample and Polish Disc

The sample is set by the placement of the pan but should be confirmed with the polish disc with the controls in manual mode.

Inspecting Position of the Sample
Figure 8.6.1

8.6.1 Inspecting Position of the Sample – Figure 8.6.1

1: **Inspection.** An alignment is as shown. With this view, the operator can be sure that the polish disc will effectively polish all portions of the sample.

Set the hand/off/auto switch to manual to engage the manual actuator switch. Switch to load to lower the polish disc onto the sample to check alignment.

9 MAINTENANCE

The Polisher is designed to provide a quality polish, maintain a long life, and low maintenance. In the event that a part needs changed or accessed, and it cannot be reached through the door, all panels can be removed. The panels **MUST** be reinstalled before any polishing, for safety and to eliminate any possible outside variables that may occur during polishing. It is important to maintain a controlled environment for polishing and accurate results. Failure to do so may result in injury, and/or results not typical of how The Polisher was designed to function.

All components of The Polisher Machine can be accessed with the panels off of the machine. When performing maintenance, make sure power is off and the main breaker for The Polisher is off. Never perform maintenance on any machine without the proper precautions. Make sure all maintenance is performed by only qualified personnel. If applying new parts to The Polisher, make sure to read instructions and follow all warnings prior to installing to avoid any issues. After installing new pieces, **ALWAYS** replace panels.

Additionally, it is good practice to keep record of maintenance to keep track of what has been done to the machine. This will help if any questions should arise and J.M. Parish Enterprises is needed for assistance.

9.1 Worm gear Speed Reducer Maintenance

Manufacturer suggests the reducer be drained from time to time (preferably while warm) and refilled to the suggested level with gear oil. Under normal environmental conditions, oil changes should take place after the initial 250 hours or every 6 months. Change oil seals when leakage or wear occurs.

9.2 Motor Maintenance

If any problems should occur, it is typically best to replace the motor with a new one.

9.3 Actuator Maintenance

If any problems should occur, it is typically best to replace the actuator with a new one.

9.4 Linear Bearing Maintenance

It is good to keep the linear bearings clean of any debris. The linear bearings are Teflon coated, so they do not need to be lubricated. Periodically wipe down shafts with water dampened rag. Apply a light coat of lubrication to the exposed ends to protect the surface.

9.5 Replacing Small Items

Reference appendix a for list of electrical materials used in The Polisher, in particular, the control panel and wiring. If there is an issue, consult an electrician or other qualified position to fix such things. Only qualified and knowledgeable personnel should access the control box at any given time.

9.6 Water System Maintenance

If the water is kept clean, the system will perform for an extended amount of time without interruption. If access blockage, look at the flow holes in the polish disc and mounting plate. If blockage persists, give the water system a good overall cleaning.

If the regulator is suspect, take the system apart; first reduce pressure in inlet and outlet lines to zero. It is not necessary to remove regulator from the line. First, pull knob back to disengage lock and turn counter-clockwise. By turning it counter-clockwise, any load on the range spring will be removed. Next, unscrew the bonnet. Make sure to unscrew carefully, as the adjusting screw and nut are not retained, so they may fall out. Remove spring and diaphragm. Unscrew and remove supply seat, pintle, and pintle spring. To clean, put parts in warm water and soap and then dry items. Blow out body using compressed air. Reassemble and readjust pressure. If the problem persists, replace the regulator.

If cleaning the regulator does not solve any flow problems, check the valve operation and/or flow meter operation.

10.0 TECHNICAL SERVICE

Do not attempt to repair beyond means or modify The Polisher in any way. Small items such as replacing light bulbs or lubrication can be handled by the operator, and larger issues can be fixed by qualified personnel. In the event that there is an issue that requires further knowledge of The Polisher, contact J.M. Parish Enterprises. **Always contact J.M. Parish Enterprises for extensive service.** For purchasing of new pieces, such as polish discs, or extensive servicing to The Polisher, please contact J.M. Parish Enterprises.

J.M. Parish Enterprises

95 16th Street

Barberton, OH 44203

Phone:

330-321-5090

11.0 TROUBLE SHOOTING AND FREQUENTLY ASKED QUESTIONS

11.1 Why is the machine not turning on?

Check to be sure the machine is properly plugged in and the breaker is on. The power on light should be illuminated. If problem persists, check to see that the E-STOP button is pulled out, and the access door is closer.

11.2 I'm in automatic mode, why won't the shaft begin polishing?

Make sure the auto mode switch is turned to run. Wait 7 seconds, the shaft begins running after a 7 second delay. If the problem still persists, be sure that the access door is shut properly.

11.3 Where do I get new polish discs? Or extensive service?

Contact J.M. Parish Enterprises at

J.M. Parish Enterprises

95 16th Street

Barberton, OH 44203

Phone:

330-321-5090

11.4 Why must the samples be 6” diameter?

6” diameter samples are standard with asphalt polishing. The Polisher was designed to use these cylinders. The sample tray and all other parts are designed for this size sample. The 6” diameter sample pressed against the sample bracket at installation assures it will be aligned with the polish disc.

11.5 Why do I need a spacer with 4” high samples?

The machine was designed to operate with a 6” high effective sample. Taller samples may experience increased pressure during the early polishing stage. Shorter samples may not receive enough pressure for polishing during the end of the polish stage. Variations are allowed, but polishing from an effective 6” (either by using a 6” high sample or a 4” high sample plus a 2” spacer) results in repeatedly consistent polishing.

11.6 Where should I place my drain hose leading from the sample tray?

The hose should lead to a proper disposal/drainage area. Keep in mind, different chemicals may be used in your sample. Contact disposal services or environmental services if you have any questions on what to do with waste.

11.7 Is it possible to change the polishing timer from one hour?

The one hour timer was set as a standard and should not be altered.

11.8 Is this machine qualified to give scientific results?

Yes. This machine properly fits into the scientific methods of testing and experimentation. It allows for consistent polishing, with controlled variables, speeds, and time. It does not measure wear on the samples, it produces a polished surface so traction can be measured using whichever scientific means as seen necessary.

11.9 Is the polisher the most efficient way to polish asphalt thus far?

Yes. Through engineering tests, this is the most efficient and consistent machine available.

11.10 Where may I bring any additional inquiries?

Contact J.M. Parish Enterprises at:

J.M. Parish Enterprises

95 16th Street

Barberton, OH 44203

Phone:

330-321-5090

12.0 ACCESSORIES

While The Polisher is fully functional and efficient, there are accessories available for convenience.

12.1 Stand

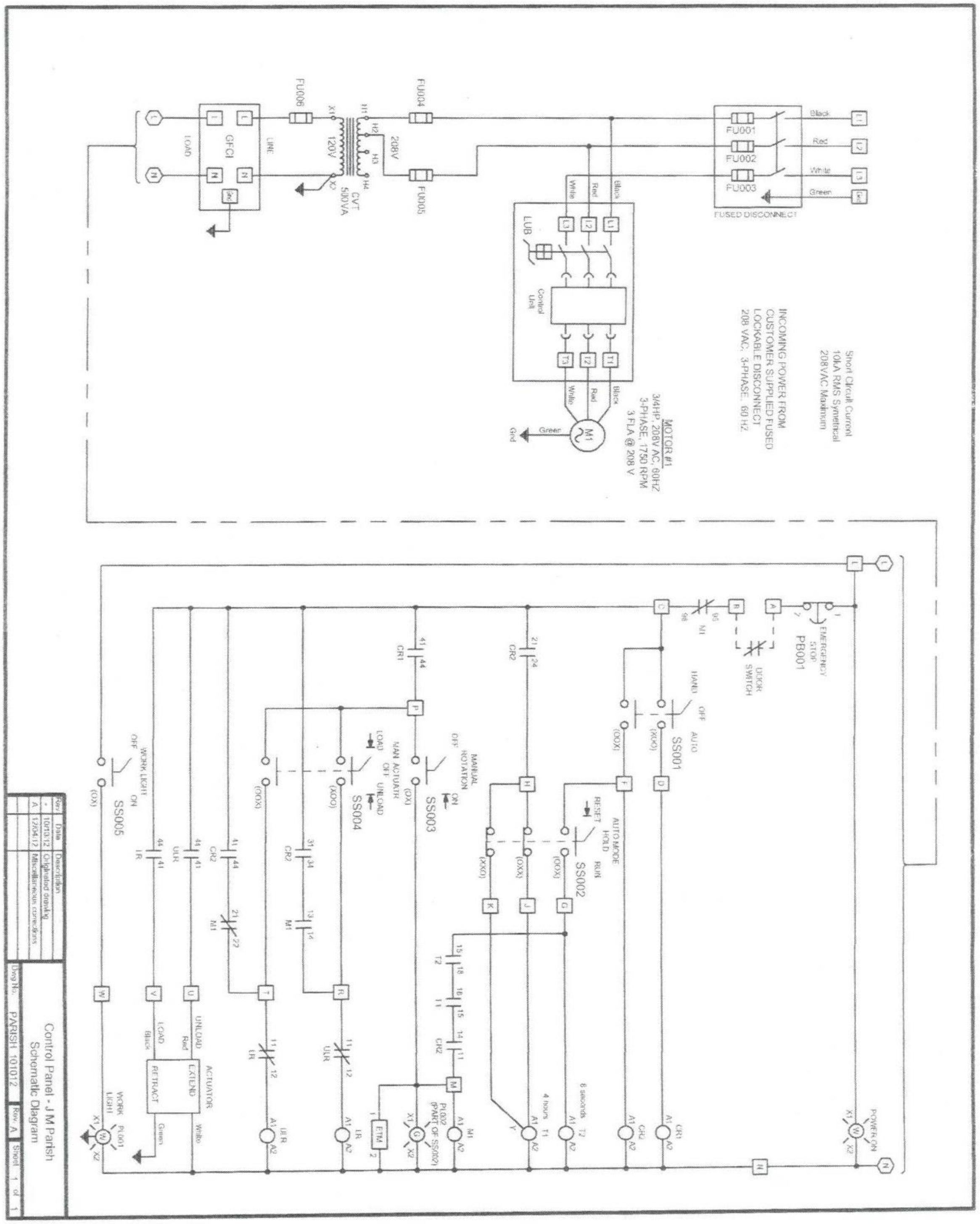
A stand that will provide a sturdy and convenient lift for The Polisher. Samples will be accessible at general eye level, and allow for easier access to all components of the machine.

12.2 Standard Sample Mold

This is either a 6” diameter by 6” high or 6” diameter by 4” high standard mold used for creating samples easily. It is recommended that this is used for consistency and ease.

Appendix

Appendix a



JM Parish Asphalt Test Panel
Project # 68-12-011

Item	CATALOG NO.	DESCRIPTION		QTY
M1	LUB12	Motor starter		1
M1	LUCA05FU	Control module - 3 Phase		1
M1	LU9SPO	Barrier		1
M1	LUA1C11	Aux contact		1
MD	GS1DU3	Fusible disconnect		1
MD	GS1AH120	Handle		1
MD	GS1AE8	Shaft		1
MD	LPJ-15SPI			3
T1	RE11RHMU	Timer, Multi Finction - Ht		1
T2	RE11RAMU	Timer, On Delay		1
Power On PL	ZB4BV013	White Pilot Light		1
Power On PL	ZB4BVG1	Mounting Brkt & contacts		1
Power On PL	ZBY2326	Nameplate		1
SS004	ZB4BJ5	Selector switch, 3 Pos. Load-Off-Unload		1
SS004	ZB4BZ103	Mounting Brkt & contacts		1
SS004	ZBZ33	Nameplate holder		1
SS004	ZBY05002	Special engraving		1
SS003	ZB4BD4	Selector switch, 2 Pos. Manual Rotation Off/On		1
SS003	ZB4BZ101	Mounting Brkt & contacts		1
SS003	ZBZ33	Nameplate holder		1
SS003	ZBY05002	Special engraving		1
SS005	ZB4BD2	Selector switch, 2 Pos. (Work Light)		1
SS005	ZB4BZ101	Mounting Brkt & contacts		1
SS005	ZBZ32	Nameplate holder		1
SS005	ZBY01002	Special engraving		1
SS001	ZB4BD3	Selector switch, 3 Pos. (H-O-A)		1
SS001	ZB4BZ103	Mounting Brkt & contacts		1
SS001	ZBY2387	Nameplate		1
SS002	ZB4BK1733	Selector switch, 3 Pos. (Auto Mode/Reset-Hold-Run)		1
SS002	ZB4BZ009	Mounting Brkt & contacts		1
SS002	ZBE101	N O Contacts		2
SS002	ZBE102	N C Contacts		2
SS002	ZBVG3	Green LED		2
SS002	ZBZ32	Nameplate holder		1
SS002	ZBY01002	Special engraving		1
SS001	ZB4BT84	Trigger action push-pull switch (E-Stop)		1
SS001	ZBY9330	E-Stop plate		1
SS001	ZB4BZ102	Mounting Brkt & NC		1

Item	CATALOG NO.	DESCRIPTION		QTY
T. B.'S	AB1VV435U	GREY 6mm TERMINAL BLOCK		24
T. B.'S	AB1VV435UBLA	BLUE 6mm TERMINAL BLOCK		4
T. B.'S	AB1AC24	GREY END BARRIER		14
T. B.'S	AB1AB8M35	Metal END CLAMP		8
T. B.'S	AB1BV6	10 BLANK 6mm MARKERS		2
T. B.'S	AB1ALN10	Jumpers		2
CVT	9070T500D20	Transformer - 480-240-208/120		1
CVT	9080FB3611CC	Fuse block		1
CVT	9070FP1	Fuse pullers		1
CVT	9070FSC2	Terminal barriers		1
CVT	FNQR 5	Primary Fuse		3
CVT	FNQR 6 1/4	Secondary fuse		2
Door Switch	XCSPA593	Door detection switch		1
Door Switch Key	XCSZ13	Door detection switch		1
Enclosure	EN4SD20166GY	Enclosure		1
Enclosure	EN4SD20166WGY	Window Door		1
Enclosure	EP2016	Mounting Plate		1
Enclosure	EHLPL	Handle		1
Ground	PK9GTA	EQUIPMENT GROUND BAR ASSY		1
LR/ULR	RPM21F7	Relays		2
LR/ULR	RPZF2	Relay Sockets - RPM		2
CR1/CR2	RXM4AB2F7	Relays		2
CR1/CR2	RXZE2M114	Relay Sockets - RXZ		2
CR1/CR2	RXZ400	Hold Down Clip		2
Work Light	RABVX100DG	Light Fixture		2
Work Light	SCF13ELMINI841	Lamp		2
GFCI	SCBGW125G	Box		1
GFCI	SCC58C16	Cover		1
GFCI	PS2081I	GFI		1
ETM	C342-2474	Elapsed Time Meter		1

Appendix b

J.M.PARISH
ENTERPRISES
The Polisher

Operation Check List

1 INSPECT POLISH DISC
2 INSTALL SAMPLE; CLAMP IN PLACE
3 INSPECT THAT THERE ARE NO OBSTACLES
4 TURN WATER ON, SET TO 100 CC/M
5 INSPECT FLOW THROUGH POLISH DISC
6 CLOSE DOOR
7 PULL EMERGENCY STOP OUT
8 TURN BREAKER ON
9 SELECT AUTO
10 SELECT RUN
11 INSPECT OPERATION THROUGH WINDOW
12 AFTER 1 HOUR, MACHINE STOPS
13 OPEN DOOR
14 REMOVE SAMPLE
15 TURN POWER AND WATER OFF
16 CLEAN MACHINE

D68-12-004-1

APPENDIX B.

JOB MIX FORMULAS

Eight pavement sections were identified in different Districts in Ohio during this research project. The selection of these pavement sections is based on the criteria that each of the pavement sections has adequate documentation of traffic counts as well as the construction materials (i.e., Job Mix Formulas) used.

The eight JMFs for the current study were selected to have a wide range of polish susceptibility: for example; three aggregate sources have possible low polish susceptibility denoted by L1, L2, and L3, four aggregate sources have possible medium polish susceptibility denoted by M1, M2, M3, and M4, and one aggregate source has possible high polish susceptibility denoted by H1.

Appendix B summarizes all eight job mix formulas (aggregate gradation, optimum binder content, and other volumetric properties of HMA) used in this research that were provided by Ohio Department of Transportation.

Table B-1: Percent passing, optimum binder content and volumetric properties for low polish susceptibility aggregate (L1)

1. Possible Low Polish (Gravel), L1			
Sieve Size	**% Passing**	**Accumulated % Retained**	**% Retained**
0.75"	100	0	0
0.5"	100	0	0
0.375"	100	0	0
No. 4	54	0.46	0.46
No. 8	36	0.64	0.18
No. 16	29	0.71	0.07
No. 30	20	0.8	0.09
No. 50	9	0.91	0.11
No. 100	5	0.95	0.04
No. 200	2.5	0.975	0.025
Pan	0	1	0.025
Optimum Asphalt Content (%)			0.063
G_{mb}			2.324
G_{mm}			2.390
Air void			0.035

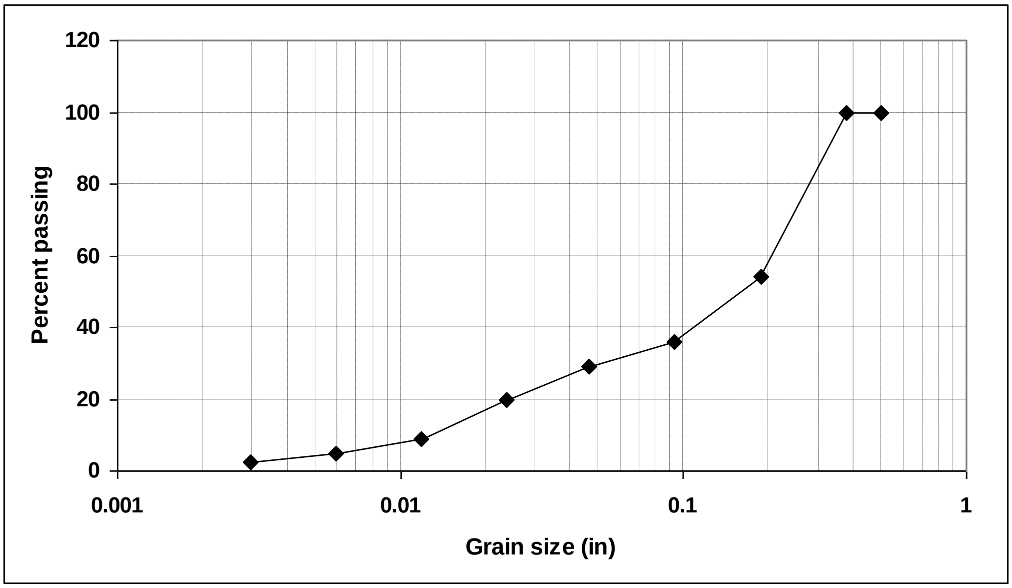


Figure B-1: Gradation curve for low polish susceptibility aggregate (L1)

Table B-2: Percent passing, optimum binder content and volumetric properties for low polish susceptibility aggregate (L2)

2. Possible Low Polish (Trap Rock), L2			
Sieve Size	**% Passing**	**Accumulated % Retained**	**% Retained**
0.75"	100	0	0
0.5"	97	0.03	0.03
0.375"	77	0.23	0.2
No. 4	47	0.53	0.3
No. 8	35	0.65	0.12
No. 16	23	0.77	0.12
No. 30	16	0.84	0.07
No. 50	10	0.9	0.06
No. 100	6	0.94	0.04
No. 200	3	0.97	0.03
Pan	0	1	0.03
Optimum Asphalt Content (%)			0.056
G_{mb}			2.118
G_{mm}			2.618
Air void			0.04

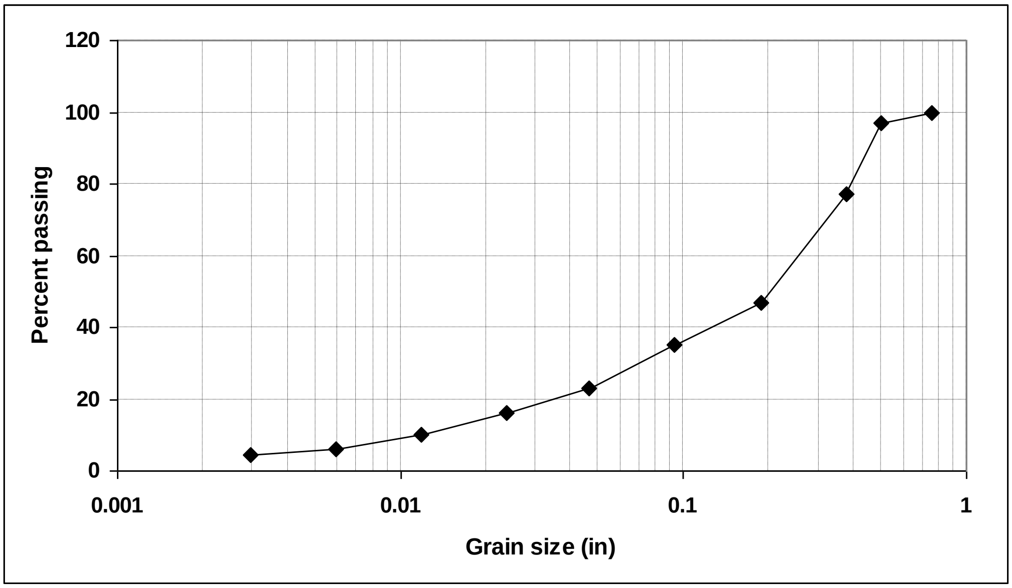


Figure B-2: Gradation curve for low polish susceptibility aggregate (L2)

Table B-3: Percent passing, optimum binder content and volumetric properties for low polish susceptibility aggregate (L3)

3. Possible Low Polish (Gravel), L3			
Sieve Size	**% Passing**	**Accumulated % Retained**	**% Retained**
0.75"	100	0	0
0.5"	100	0	0
0.375"	99	0.01	0.01
No. 4	55	0.45	0.44
No. 8	38	0.62	0.17
No. 16	26	0.74	0.12
No. 30	16	0.84	0.1
No. 50	6	0.94	0.1
No. 100	2	0.98	0.04
No. 200	1.6	0.984	0.004
Pan	0	1	0.016
Optimum Asphalt Content (%)			0.063
G_{mb}			2.302
G_{mm}			2.386
Air void			0.035

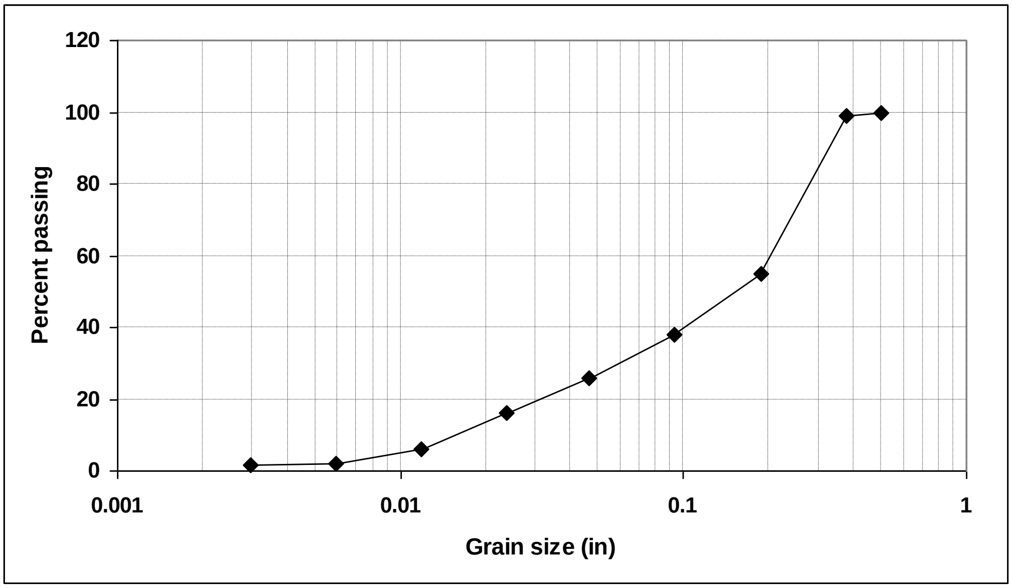


Figure B-3: Gradation curve for low polish susceptibility aggregate (L3)

Table B-4: Percent passing, optimum binder content and volumetric properties for medium polish susceptibility aggregate (M1)

4. Possible Medium Polish (Limestone), M1			
Sieve Size	**% Passing**	**Accumulated % Retained**	**% Retained**
0.75"	100	0	0
0.5"	100	0	0
0.375"	96	0.04	0.04
No. 4	57	0.43	0.39
No. 8	33	0.67	0.24
No. 16	21	0.79	0.12
No. 30	14	0.86	0.07
No. 50	10	0.9	0.04
No. 100	6	0.94	0.04
No. 200	2	0.98	0.04
Pan	0	1	0.02
Optimum Asphalt Content (%)			0.059
G_{mb}			2.352
G_{mm}			2.435
Air void			0.035

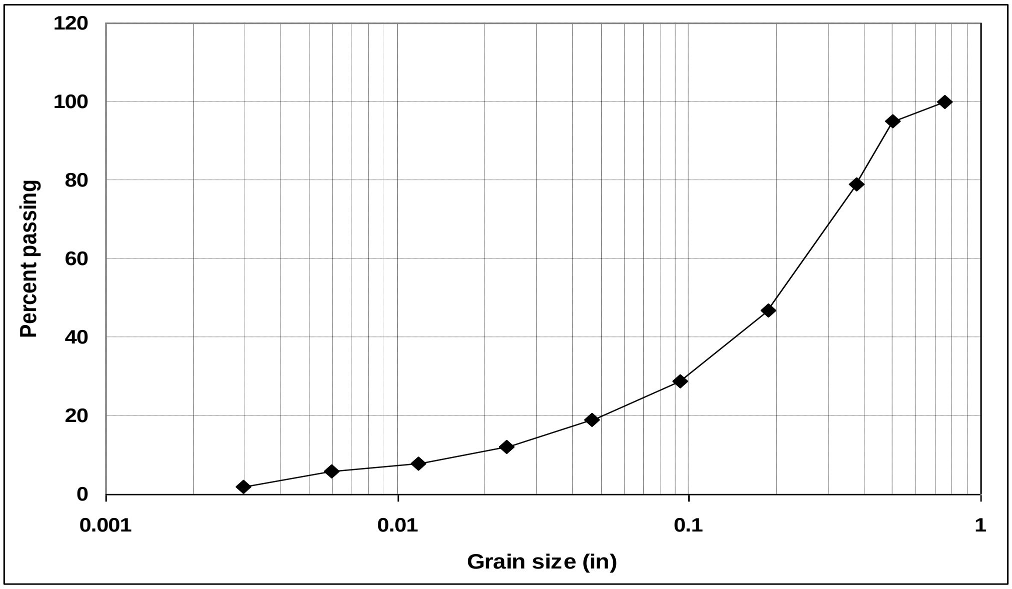


Figure B-4: Gradation curve for medium polish susceptibility aggregate (M1)

Table B-5: Percent passing, optimum binder content and volumetric properties for medium polish susceptibility aggregate (M2)

5. Possible Medium Polish (Limestone), M2			
Sieve Size	% Passing	Accumulated % Retained	% Retained
0.75"	100	0	0
0.5"	100	0	0
0.375"	96	0.04	0.04
No. 4	57	0.43	0.39
No. 8	33	0.67	0.24
No. 16	21	0.79	0.12
No. 30	14	0.86	0.07
No. 50	10	0.9	0.04
No. 100	6	0.94	0.04
No. 200	2	0.98	0.04
Pan	0	1	0.02
Optimum Asphalt Content (%)			0.061
G_{mb}			2.352
G_{mm}			2.452
Air void			0.04

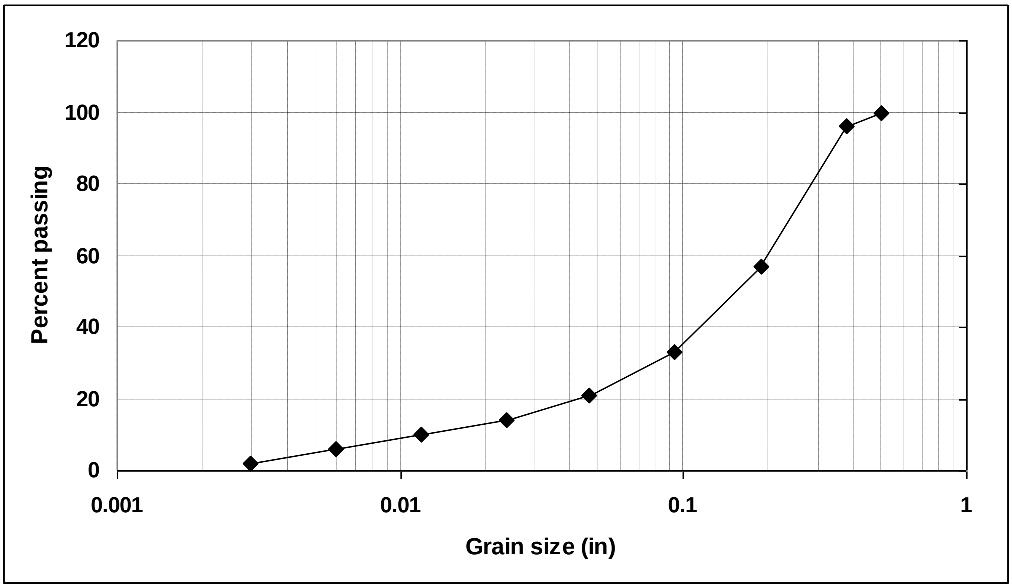


Figure B-5: Gradation curve for medium polish susceptibility aggregate (M2)

Table B-6: Percent passing, optimum binder content and volumetric properties for medium polish susceptibility aggregate (M3)

6. Possible Medium Polish (Dolomite), M3			
Sieve Size	**% Passing**	**Accumulated % Retained**	**% Retained**
0.75"	100	0	0
0.5"	100	0	0
0.375"	98	0.02	0.02
No. 4	62	0.38	0.36
No. 8	37	0.63	0.25
No. 16	23	0.77	0.14
No. 30	15	0.85	0.08
No. 50	10	0.9	0.05
No. 100	7	0.93	0.03
No. 200	4.6	0.954	0.024
Pan	0	1	0.046
Optimum Asphalt Content (%)			0.056
G_{mb}			2.451
G_{mm}			2.549
Air void			0.04

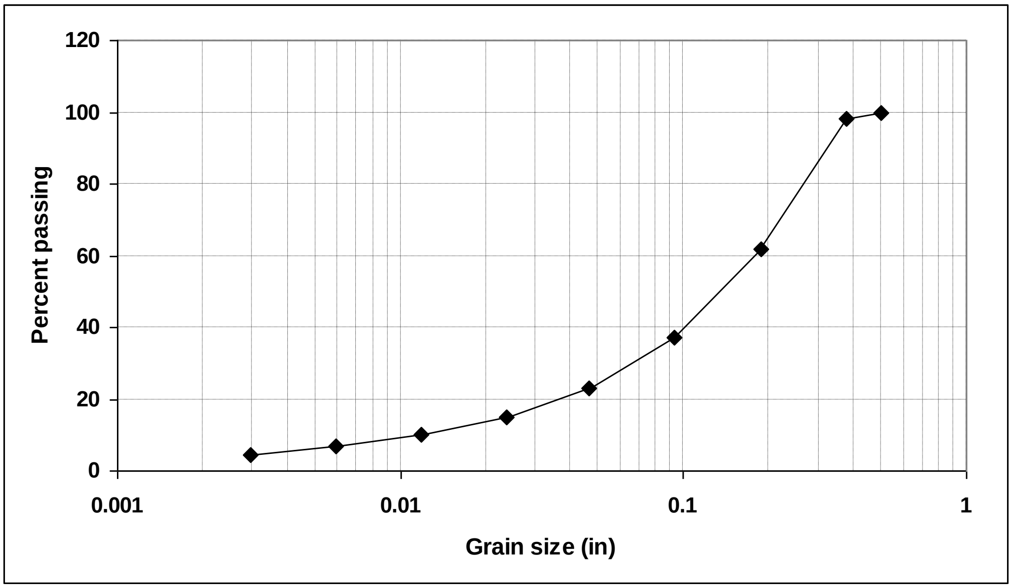


Figure B-6: Gradation curve for medium polish susceptibility aggregate (M3)

Table B-7: Percent passing, optimum binder content and volumetric properties for medium polish susceptibility aggregate (M4)

7. Possible Medium Polish (Dolomite), M4			
Sieve Size	**% Passing**	**Accumulated % Retained**	**% Retained**
0.75"	100	0	0
0.5"	100	0	0
0.375"	96	0.04	0.04
No. 4	61	0.39	0.35
No. 8	41	0.59	0.2
No. 16	26	0.74	0.15
No. 30	17	0.83	0.09
No. 50	10	0.9	0.07
No. 100	7	0.93	0.03
No. 200	5.2	0.948	0.018
Pan	0	1	0.052
Optimum Asphalt Content (%)			0.059
G_{mb}			2.417
G_{mm}			2.521
Air void			0.04

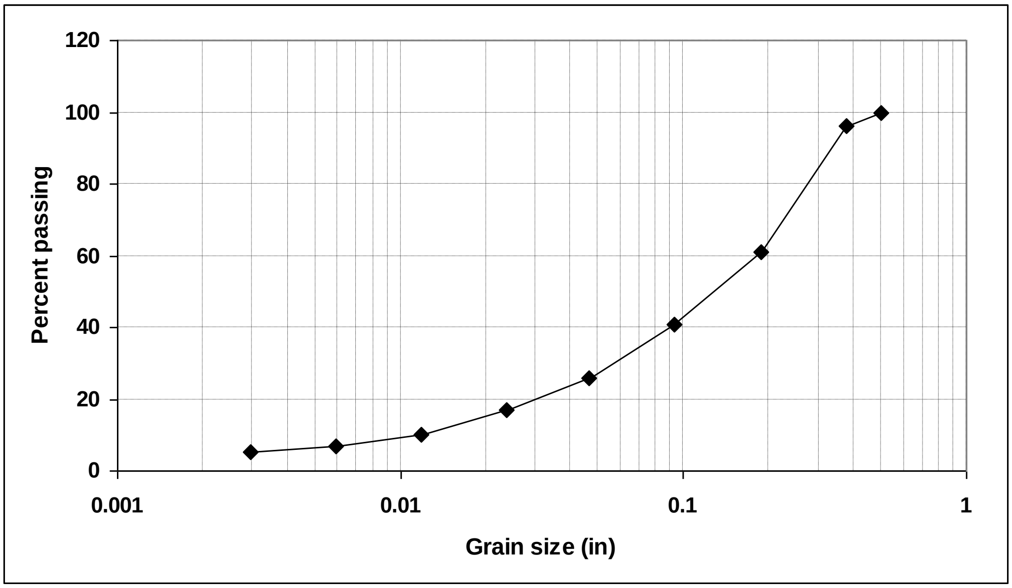


Figure B-7: Gradation curve for medium polish susceptibility aggregate (M4)

Table B-8: Percent passing, optimum binder content and volumetric properties for high polish susceptibility aggregate (H1)

8. Possible High Polish (Limestone), H1			
Sieve Size	**% Passing**	**Accumulated % Retained**	**% Retained**
0.75"	100	0	0
0.5"	97	0.03	0.03
0.375"	85	0.15	0.12
No. 4	48	0.52	0.37
No. 8	35	0.65	0.13
No. 16	27	0.73	0.08
No. 30	18	0.82	0.09
No. 50	8	0.92	0.1
No. 100	4	0.96	0.04
No. 200	3	0.97	0.01
Pan	0	1	0.03
Optimum Asphalt Content (%)			0.056
G_{mb}			2.361
G_{mm}			2.450
Air void			0.035

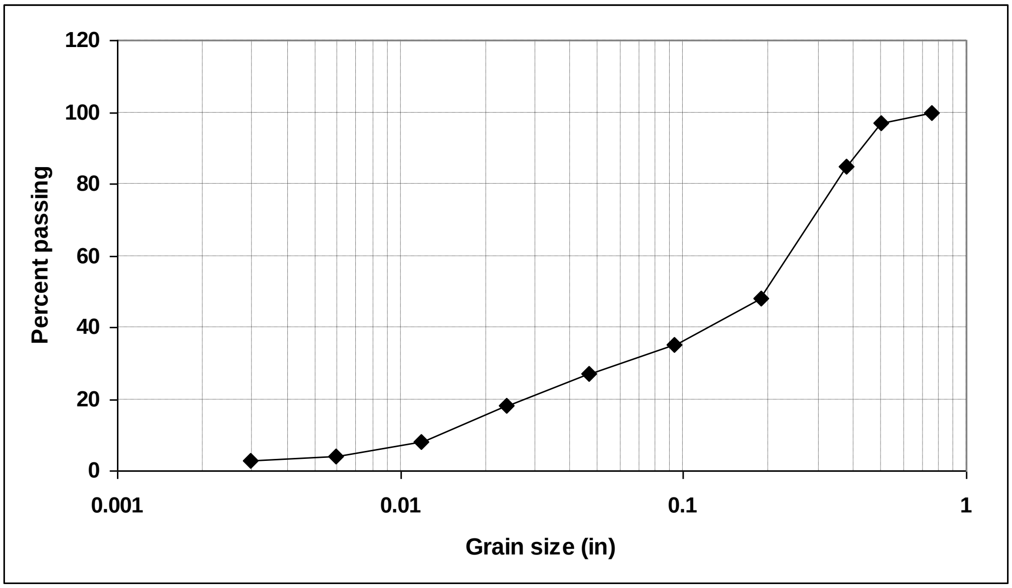


Figure B-8: Gradation curve for high polish susceptibility aggregate (H1)

APPENDIX C.

LABORATORY TEST RESULTS

The laboratory-prepared gyratory-compacted HMA specimens are polished for eight hours using the developed accelerated polishing machine. Specimens are then tested after each hour of polishing by the British pendulum tester and sand patch method. Three specimens are tested for each JMF and their average is reported as the BPN and MTD, which is a measure of the polish value and macrotexture, respectively.

Appendix C provides information on numerical values of the BPN and MTD for each hour of polishing for all eight hours using the eight different JMFs labelled according to their polish susceptibility. For all the JMFs studied, a residual friction (BPN) and macrotexture (MTD) values are found to be reached at the end of eight hours of polishing.

Table C-1: BPN for 8-hour polishing for job mix formula # 1 (L1)

Sample #	Trials	Time (min.)								
		0	60	120	180	240	300	360	420	480
1	1	74	63	60	58	58	58	58	58	57
	2	74	63	60	59	58	58	58	58	58
	3	72	63	59	59	57	57	58	57	58
	4	72	63	59	58	57	58	57	57	57
	Average	73.00	63.00	59.50	58.50	57.50	57.75	57.75	57.50	57.50
2	1	72	64	63	61	60	59	59	59	59
	2	71	64	63	61	60	59	59	58	59
	3	71	64	63	61	60	60	59	59	58
	4	70	63	62	60	59	59	59	58	58
	Average	71.00	63.75	62.75	60.75	59.75	59.25	59.00	58.50	58.50
3	1	76	69	66	62	62	59	60	60	60
	2	76	70	65	63	61	60	60	60	60
	3	75	69	66	62	60	60	59	59	60
	4	74	70	65	63	60	59	59	60	60
	Average	75.25	69.50	65.50	62.50	60.75	59.50	59.50	59.75	60.00
Final BPN		73.08	65.42	62.58	60.58	59.33	58.83	58.75	58.58	58.67

Table C-2: MTD for 8-hour polishing for job mix formula # 1 (L1)

Sample #	Time (min.)								
	0	**60**	**120**	**180**	**240**	**300**	**360**	**420**	**4800**
1	0.940	0.928	0.882	0.870	0.880	0.861	0.859	0.861	0.861
2	0.909	0.879	0.862	0.853	0.855	0.851	0.852	0.850	0.851
3	0.790	0.743	0.725	0.701	0.696	0.705	0.708	0.695	0.690
Average MTD	0.880	0.850	0.823	0.808	0.810	0.806	0.806	0.802	0.801

Table C-3: BPN for 8-hour polishing for job mix formula # 2 (L2)

Sample #	Trials	Time (min.)								
		0	60	120	180	240	300	360	420	480
1	1	77	65	61	61	59	58	59	59	60
	2	76	64	61	61	59	58	60	60	59
	3	76	65	62	60	59	60	59	59	59
	4	76	64	61	60	59	60	60	60	59
	Average	76.25	64.50	61.25	60.50	59.00	59.00	59.50	59.50	59.25
2	1	78	66	62	62	59	60	59	59	60
	2	79	66	63	62	59	60	59	60	60
	3	78	66	63	62	59	60	58	60	59
	4	79	66	62	62	59	60	59	59	59
	Average	78.50	66.00	62.50	62.00	59.00	60.00	58.75	59.50	59.50
3	1	74	66	63	62	59	57	58	58	59
	2	75	67	64	61	60	57	58	59	59
	3	75	67	63	61	60	59	58	59	58
	4	75	67	63	62	59	58	58	59	59
	Average	74.75	66.75	63.25	61.50	59.50	57.75	58.00	58.75	58.75
Final BPN		76.50	65.75	62.33	61.33	59.17	58.92	58.75	59.25	59.17

Table C-4: MTD for 8-hour polishing for job mix formula # 2 (L2)

Sample #	Time (min.)								
	0	**60**	**120**	**180**	**240**	**300**	**360**	**420**	**4800**
1	1.490	1.220	1.170	1.110	1.100	1.040	0.990	0.984	0.980
2	1.440	1.155	1.098	1.069	1.041	1.027	1.028	1.026	1.026
3	1.591	1.311	1.256	1.200	1.174	1.121	1.087	1.077	1.081
Average MTD	1.507	1.229	1.175	1.126	1.105	1.063	1.035	1.029	1.029

Table C-5: BPN for 8-hour polishing for job mix formula # 3 (L3)

Sample #	Trials	Time (min.)								
		0	60	120	180	240	300	360	420	480
1	1	73	67	63	63	62	62	59	60	60
	2	72	67	64	62	63	61	60	59	60
	3	72	66	63	62	62	61	61	60	59
	4	71	66	64	62	60	61	60	60	59
	Average	72.00	66.50	63.50	62.25	61.75	61.25	60.00	59.75	59.50
2	1	74	67	63	63	63	62	59	60	61
	2	74	67	64	63	62	62	59	61	60
	3	75	67	64	63	61	61	60	60	60
	4	74	67	65	63	62	60	60	60	59
	Average	74.25	67.00	64.00	63.00	62.00	61.25	59.50	60.25	60.00
3	1	72	64	62	61	59	60	59	60	60
	2	70	65	62	61	59	60	58	60	60
	3	72	65	62	61	59	62	60	60	59
	4	71	64	62	61	61	59	59	59	60
	Average	71.25	64.50	62.00	61.00	59.50	60.25	59.00	59.75	59.75
Final BPN		72.50	66.00	63.17	62.08	61.08	60.92	59.50	59.92	59.75

Table C-6: MTD for 8-hour polishing for job mix formula # 3 (L3)

Sample #	Time (min.)								
	0	60	120	180	240	300	360	420	480
1	0.997	0.912	0.891	0.884	0.874	0.892	0.881	0.874	0.871
2	0.966	0.894	0.863	0.847	0.845	0.833	0.822	0.820	0.811
3	1.037	0.962	0.951	0.911	0.920	0.903	0.921	0.893	0.900
Average MTD	1.000	0.923	0.902	0.881	0.880	0.876	0.875	0.862	0.861

Table C-7: BPN for 8-hour polishing for job mix formula # 4 (M1)

Sample #	Trials	Time (min.)								
		0	60	120	180	240	300	360	420	480
1	1	73	67	62	60	59	58	55	55	55
	2	73	66	62	60	59	57	55	55	54
	3	74	66	62	60	58	56	55	54	55
	4	73	66	61	59	58	55	55	53	53
	Average	73.25	66.25	61.75	59.75	58.50	56.50	55.00	54.25	54.25
2	1	74	68	63	60	59	58	57	55	54
	2	75	67	63	60	59	59	57	55	54
	3	75	68	63	60	59	58	56	54	54
	4	75	67	62	59	60	58	55	54	54
	Average	74.75	67.50	62.75	59.75	59.25	58.25	56.25	54.50	54.00
3	1	75	70	62	59	57	56	56	55	55
	2	75	70	60	58	56	56	56	55	55
	3	76	69	60	58	56	55	56	55	54
	4	76	69	60	58	55	55	56	54	54
	Average	75.50	69.50	60.50	58.25	56.00	55.50	56.00	54.75	54.50
Final BPN		74.50	67.75	61.67	59.25	57.92	56.75	55.75	54.50	54.25

Table C-8: MTD for 8-hour polishing for job mix formula # 4 (M1)

Sample #	**Time (min.)**								
	0	**60**	**120**	**180**	**240**	**300**	**360**	**420**	**4800**
1	1.509	1.355	1.208	1.133	1.095	1.109	1.152	1.113	1.104
2	1.488	1.255	1.250	1.225	1.198	1.125	1.045	1.022	1.026
3	1.585	1.504	1.401	1.355	1.325	1.318	1.304	1.288	1.281
Average MTD	1.527	1.371	1.286	1.238	1.206	1.184	1.167	1.141	1.137

Table C-9: BPN for 8-hour polishing for job mix formula # 5 (M2)

Sample #	Trials	Time (min.)								
		0	60	120	180	240	300	360	420	480
1	1	78	72	68	63	59	56	55	55	55
	2	77	72	68	62	59	56	55	55	55
	3	77	72	67	62	58	57	55	55	54
	4	77	71	67	61	58	57	54	54	54
	Average	77.25	71.25	67.50	62.00	58.50	56.50	54.75	54.75	54.50
2	1	76	72	69	65	63	60	58	55	56
	2	75	71	70	66	63	60	59	56	55
	3	76	71	69	65	62	60	58	56	55
	4	75	71	70	66	63	60	58	56	55
	Average	75.50	71.25	69.50	65.50	62.75	60.00	58.25	55.75	55.25
3	1	78	70	65	63	59	57	55	54	55
	2	77	69	64	64	59	58	56	53	55
	3	77	69	65	64	58	58	55	54	54
	4	77	69	65	63	58	58	56	56	54
	Average	77.25	69.25	64.75	63.50	58.50	57.75	55.50	54.25	54.50
Final BPN		76.67	70.75	67.25	63.67	59.92	58.08	56.17	54.92	54.75

Table C-10: MTD for 8-hour polishing for job mix formula # 5 (M2)

Sample #	Time (min.)								
	0	60	120	180	240	300	360	420	4800
1	0.993	0.950	0.922	0.880	0.856	0.832	0.807	0.796	0.793
2	1.062	0.943	0.903	0.887	0.870	0.871	0.852	0.846	0.832
3	1.030	0.932	0.882	0.846	0.839	0.846	0.821	0.818	0.811
Average MTD	1.028	0.942	0.902	0.871	0.855	0.850	0.827	0.820	0.812

Table C-11: BPN for 8-hour polishing for job mix formula # 6 (M3)

Sample #	Trials	Time (min.)								
		0	60	120	180	240	300	360	420	480
1	1	76	68	63	60	60	58	56	56	57
	2	76	68	64	61	60	56	56	56	56
	3	75	69	63	60	59	57	56	55	56
	4	75	69	64	61	59	56	57	55	56
	Average	75.50	68.50	63.50	60.50	59.50	56.75	56.25	55.50	56.25
2	1	76	68	62	59	58	56	54	55	55
	2	77	68	64	61	57	57	54	54	54
	3	77	67	62	61	59	57	54	55	54
	4	76	67	63	60	59	55	54	54	54
	Average	76.50	67.50	62.75	60.25	58.25	56.25	54.00	54.50	54.25
3	1	78	68	63	59	59	55	55	53	54
	2	78	68	64	60	57	54	55	54	54
	3	78	68	63	60	59	56	54	55	54
	4	79	67	64	60	58	56	54	54	55
	Average	78.25	67.75	63.50	59.75	58.25	55.25	54.50	54.00	54.25
Final BPN		76.75	67.92	63.25	60.17	58.67	56.08	54.92	54.67	54.92

Table C-12: MTD for 8-hour polishing for job mix formula # 6 (M3)

Sample #	Time (min.)								
	0	60	120	180	240	300	360	420	4800
1	1.105	0.931	0.892	0.865	0.563	0.842	0.827	0.841	0.833
2	1.071	0.921	0.851	0.831	0.812	0.791	0.812	0.801	0.801
3	1.151	1.021	0.914	0.892	0.864	0.871	0.856	0.827	0.830
Average MTD	1.109	0.958	0.886	0.863	0.746	0.835	0.832	0.823	0.821

Table C-13: BPN for 8-hour polishing for job mix formula # 7 (M4)

Sample #	Trials	Time (min.)								
		0	60	120	180	240	300	360	420	480
1	1	79	70	63	60	58	55	53	53	54
	2	77	69	63	61	58	54	54	53	53
	3	78	69	63	60	58	55	54	53	53
	4	76	69	63	60	58	54	54	53	53
	Average	77.50	69.25	63.00	60.25	58.00	54.50	53.75	53.00	53.25
2	1	76	68	61	60	58	55	54	53	52
	2	75	67	62	61	57	54	53	53	53
	3	76	67	61	59	57	53	53	51	53
	4	76	67	62	59	58	53	54	52	53
	Average	75.75	67.25	61.50	59.75	57.50	53.75	53.50	52.25	52.75
3	1	75	68	64	58	56	54	52	53	51
	2	75	69	63	58	56	54	52	51	51
	3	75	67	63	59	56	54	53	51	52
	4	75	67	63	58	56	54	53	53	53
	Average	75.00	67.75	63.25	58.25	56.00	54.00	52.50	52.00	51.75
Final BPN		76.08	68.08	62.58	59.42	57.17	54.08	53.25	52.42	52.58

Table C-14: MTD for 8-hour polishing for job mix formula # 7 (M4)

Sample #	Time (min.)								
	0	60	120	180	240	300	360	420	480
1	1.136	0.966	0.856	0.836	0.836	0.826	0.836	0.816	0.806
2	0.971	0.792	0.801	0.810	0.783	0.773	0.780	0.764	0.771
3	1.080	0.931	0.812	0.810	0.830	0.802	0.794	0.785	0.777
Average MTD	1.062	0.896	0.823	0.819	0.816	0.800	0.803	0.788	0.785

Table C-15: BPN for 8-hour polishing for job mix formula # 8 (H1)

Sample #	Trials	Time (min.)								
		0	60	120	180	240	300	360	420	480
1	1	71	61	53	49	47	48	47	47	46
	2	70	60	53	49	47	47	46	45	46
	3	69	60	52	49	47	48	47	45	47
	4	70	60	52	49	47	47	46	45	47
	Average	70.00	60.25	52.50	49.00	47.00	47.50	46.50	45.50	46.50
2	1	74	61	56	51	49	47	50	49	47
	2	73	63	55	50	48	48	49	47	48
	3	72	63	54	50	49	49	49	47	47
	4	71	62	54	51	49	48	49	47	48
	Average	72.50	62.25	54.75	50.50	48.75	48.00	49.25	47.50	47.50
3	1	70	57	52	47	45	43	44	45	44
	2	69	58	51	46	44	44	45	43	43
	3	69	56	50	46	45	45	44	43	44
	4	68	56	50	47	45	44	43	43	43
	Average	69.00	56.75	50.75	46.50	44.75	44.00	44.00	43.50	43.50
Final BPN		70.50	59.75	52.67	48.67	46.83	46.50	46.58	45.50	45.83

Table C-16: MTD for 8-hour polishing for job mix formula # 8 (H1)

Sample #	Time (min.)								
	0	**60**	**120**	**180**	**240**	**300**	**360**	**420**	**480**
1	1.407	1.099	1.009	0.981	0.976	0.964	0.990	0.960	0.963
2	1.443	1.144	0.1.051	1.032	1.041	1.013	1.016	1.030	1.021
3	1.320	1.010	0.894	0.862	0.857	0.880	0.863	0.855	0.860
Average MTD	1.390	1.084	0.952	0.958	0.958	0.952	0.956	0.948	0.948

APPENDIX D.

Raw Data of Field Measurements

Harrison R22-(L1) 2007						
Rout	**Mile marker**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
22East	5.28	45.6	0.500	0.660	0.600	NA
22East	5.75	48.3	0.450	0.693	0.580	NA
22East	6.25	44.4	0.470	0.615	0.620	NA
22East	6.75	44.4	0.550	0.660	0.640	NA
22East	7.25	46.8	0.500	0.672	0.570	NA
22East	7.76	50.8	0.500	0.655	0.640	NA
Mean		46.7	0.495	0.65	0.608	NA
Standard Deviation		2.5	0.038	0.035	0.03	NA
22West	5.26	49.4	0.52	0.687	0.615	NA
22West	5.75	50.6	0.46	0.663	0.697	NA
22West	6.27	48.8	0.45	0.390	0.739	NA
22West	6.75	48.7	0.58	0.654	0.671	NA
22West	7.26	51.2	0.45	0.684	0.600	NA
22West	7.76	47.5	0.48	0.633	0.616	NA
Mean		49.4	0.49	0.67	0.656	NA
Standard Deviation		1.3	0.055	0.023	0.055	NA

Harrison R22-(L1) 2008						
Rout	**Mile marker**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
22East	5.28	50.076	0.540	0.629	0.540	62.2
22East	5.75	52.749	0.430	0.704	0.562	65.8
22East	6.25	53.442	0.430	0.643	0.524	60.2
22East	6.75	51.759	0.500	0.699	0.580	67.4
22East	7.25	54.036	0.450	0.651	0.540	64
22East	7.76	53.64	0.460	0.633	0.550	58.8
Mean		52.617	0.468	0.66	0.549	63.1
Standard Deviation		1.479931	0.029	0.033	0.02	3.3
22West	5.26	55.026	0.580	0.668	0.575	61.2
22West	5.75	54.63	0.400	0.657	0.552	63.2
22West	6.27	53.937	0.450	0.703	0.590	60.6
22West	6.75	54.234	0.570	0.694	0.590	63.4
22West	7.26	55.521	0.420	0.744	0.612	66
22West	7.76	51.165	0.410	0.661	0.533	63.8
Mean		54.08	0.472	0.688	0.575	63
Standard Deviation		1.5	0.07	0.033	0.029	1.94

Harrison R22-(L1) 2009						
Rout	**Mile marker**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
22East	5.28	50.778	0.550	0.624	0.520	62
22East	5.75	53.456	0.460	0.581	0.550	62
22East	6.25	50.778	0.420	0.674	0.540	66
22East	6.75	53.353	0.490	0.693	0.540	68
22East	7.25	54.383	0.560	0.769*	0.520	65
22East	7.76	49.748	0.550	0.684	0.530	71
Mean		52.08	0.505	0.671	0.533	65.7
Standard Deviation		1.87	0.06	0.055	0.012	3.5
22West	5.26	53.25	0.630	0.64	0.581	64
22West	5.75	56.031	0.600	0.7	0.614	65
22West	6.27	55.722	0.550	0.665	0.631	66
22West	6.75	57.885	0.640	0.69	0.670	66
22West	7.26	56.546	0.640	0.64	0.685	66
22West	7.76	52.838	0.610	0.655	0.614	65
Mean		55.37	0.612	0.665	0.633	65.3
Standard Deviation		1.95	0.037	0.025	0.039	0.8

Harrison R22-(L1) 2010						
Rout	Mile marker	LWST	CTM	DFT		BPT
		SN	MPD	DFT20	DFT64	BPN
22East	5.28	51.8	0.410	0.656	0.560	53
22East	5.75	55.4	0.360	0.696	0.600	58
22East	6.25	49.5	0.370	0.671	0.610	62
22East	6.75	51.3	0.580	0.695	0.620	65
22East	7.25	54.2	0.380	0.629	0.480	66
22East	7.76	53.7	0.310	0.568	0.530	65
Mean		52.65	0.402	0.653	0.567	61.5
Standard Deviation		2.16	0.104	0.048	0.054	5
22West	5.26	53.9	0.380	0.624	0.496	64
22West	5.75	53.6	0.290	0.581	0.453	62
22West	6.27	56.7	0.610	0.674	0.534	67
22West	6.75	56.2	0.700	0.693	0.562	68
22West	7.26	56.2	0.700	0.769	0.624	70
22West	7.76	54.4	0.550	0.684	0.573	69
Mean		55.2	0.538	0.671	0.540	66.7
Standard Deviation		1.35	0.169	0.064	0.06	3

Harrison R22-(L1) 2011						
Rout	**Mile marker**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
22East	5.28	50.407	0.470	0.662	0.560	82
22East	5.75	56.421	0.450	0.640	0.600	78
22East	6.25	54.384	0.400	0.650	0.610	80
22East	6.75	44.684	0.480	0.640	0.620	75
22East	7.25	40.998	0.400	0.610	0.480	65
22East	7.76	34.402*	0.410	0.640	0.530	73
Mean		46.88	0.435	0.640	0.657	75.5
Standard Deviation		8.42	0.036	0.017	0.054	6
22West	5.26	44.878	0.390	0.600	0.500	72
22West	5.75	57.1	0.300	0.590	0.480	76
22West	6.27	50.795	0.630	0.700	0.610	76
22West	6.75	57.1	0.600	0.680	0.558	78
22West	7.26	52.44	0.590	0.615	0.530	69
22West	7.76	43.423	0.570	0.710	0.610	78
Mean		50.95	0.513	0.649	0.548	74.8
Standard Deviation		5.85	0.135	0.064	0.055	6

Harrison R22-(L1) 2012						
Rout	**Mile marker**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
22East	5.28	53.5	0.340	0.608	0.491	72
22East	5.75	60	0.290	0.679	0.583	67
22East	6.25	61	0.480	0.610	0.523	69
22East	6.75	57	0.380	0.620	0.516	80
22East	7.25	59	0.430	0.475	0.387	78
22East	7.76	48.5	0.380	0.577	0.520	70
Mean		56.5	0.383	0.595	0.503	72.7
Standard Deviation		4.7	0.07	0.068	0.065	5.2
22West	5.26	57	0.34	0.548	0.467	66
22West	5.75	54	0.29	0.583	0.503	71
22West	6.27	58	0.48	0.630	0.510	72
22West	6.75	60	0.38	0.675	0.515	74
22West	7.26	67	0.37	0.655	0.542	73
22West	7.76	49	0.380	0.633	0.570	73
Mean		57.5	0.373	0.621	0.467	71.5
Standard Deviation		6.025	0.067	0.047	0.035	2.8

Harrison R250(L3)-2007						
Rout	Mile Marker	LWST	CTM	DFT		BPT
		SN	MPD	DFT20	DFT64	BPN
250 East	23	47	0.600	0.527	0.425	NA
250 East	23.5	48.1	0.650	0.571	0.469	NA
250 East	24	48.8	0.620	0.544	0.442	NA
250 East	24.5	50	0.670	0.646	0.529	NA
250 East	25	52	0.710	0.725	0.601	NA
Mean		49.2	0.65	0.603	0.493	NA
Standard Deviation		1.9	0.043	0.082	0.072	NA
250 West	23	46.8	0.580	0.594	0.500	NA
250 West	23.5	43.1	0.600	0.544	0.450	NA
250 West	24	50.6	0.610	0.614	0.520	NA
250 West	24.5	46.9	0.750	0.584	0.488	NA
250 West	25	48.2	0.520	0.622	0.500	NA
Mean		47.2	0.612	0.592	0.492	NA
Standard Deviation		2.8	0.085	0.031	0.026	NA

Harrison R250(L3)-2008						
Rout	**Mile Marker**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
250 East	23	51.9	0.660	0.613	0.518	55.2
250 East	23.5	54	0.750	0.550	0.482	57
250 East	24	54	0.710	0.599	0.513	60.4
250 East	24.5	53.5	0.690	0.654	0.564	64.2
250 East	25	53.7	0.810	0.714	0.622	65
Mean		53.4	0.724	0.626	0.54	60.4
Standard Deviation		0.9	0.058	0.062	0.054	4.3
250 West	23	54	0.660	0.552	0.493	54.2
250 West	23.5	53.9	1.040*	0.641	0.579	59.8
250 West	24	52.9	0.600	0.579	0.509	57.2
250 West	24.5	54.1	0.810	0.664	0.594	66.2
250 West	25	52.7	0.640	0.626	0.540	65
Mean		53.5	0.75	0.612	0.543	60.5
Standard Deviation		0.7	0.181	0.046	0.043	5.1

Harrison R250(L3)-2009						
Rout	**Mile Marker**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
250 East	23	52.8	0.740	0.595	0.493	63
250 East	23.5	47.9	0.720	0.538	0.444	54
250 East	24	49	0.850	0.606	0.516	62
250 East	24.5	51.3	0.800	0.653	0.548	71
250 East	25	54.3	0.780	0.705	0.606	70
Mean		51.1	0.778	0.619	0.521	64
Standard Deviation		2.6	0.051	0.063	0.061	6.9
250 West	23	52.3	0.730	0.532	0.435	54
250 West	23.5	47.3	0.780	0.525	0.459	49
250 West	24	51	0.760	0.549	0.471	53
250 West	24.5	51	0.830	0.693	0.603	62
250 West	25	53.4	0.680	0.713	0.595	63
Mean		51	0.756	0.602	0.513	56.2
Standard Deviation		2.3	0.056	0.093	0.08	6.1

Harrison R250(L3)-2010						
Rout	**Mile Marker**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
250 East	23	49.5	0.780	0.651	0.546	61
250 East	23.5	53.2	0.880	0.525	0.458	60
250 East	24	49.7	0.830	0.562	0.481	60
250 East	24.5	52.2	0.760	0.673	0.553	62
250 East	25	52.3	0.780	0.678	0.565	64
Mean		51.4	0.806	0.618	0.521	61.4
Standard Deviation		1.7	0.049	0.07	0.048	1.7
250 West	23	49.5	0.900*	0.673	0.578	63
250 West	23.5	50.6	1.110*	0.624	0.543	62
250 West	24	52.2	0.910*	0.655	0.541	63
250 West	24.5	52.7	0.790	0.685	0.572	66
250 West	25	51	0.630	0.661	0.551	65
Mean		51.2	0868	0.66	0.557	63.8
Standard Deviation		1.3	0.176	0.023	0.017	1.6

Harrison R250(L3)-2011						
Rout	**Mile Marker**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
250 East	23	49.8	0.790	0.640	0.540	71
250 East	23.5	47.4	0.790	0.580	0.480	65
250 East	24	47.3	0.790	0.560	0.510	68
250 East	24.5	48.6	0.910	0.650	0.560	72
250 East	25	50.9	0.860	0.730	0.630	71
Mean		48.8	0.828	0.632	0.544	69.4
Standard Deviation		1.6	0.055	0.067	0.057	2.9
250 West	23	49.6	1.030*	0.722	0.654	76
250 West	23.5	46.2	1.070*	0.653	0.615	73
250 West	24	50.4	0.760	0.646	0.615	70
250 West	24.5	48.5	0.900	0.663	0.601	72
250 West	25	47.9	0.770	0.705	0.620	76
Mean		48.5	0.906	0.678	0.621	73.4
Standard Deviation		1.6	0.143	0.034	0.02	2.6

Harrison R250-2012						
Rout	**Mile Marker**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
250 East	23	49.0*	0.7	0.574	0.52	66.3
250 East	23.5	54	1.080*	0.487	0.450	62.5
250 East	24	55	0.89	0.496	0.450	72.8
250 East	24.5	54	0.79	0.612	0.540	7300
250 East	25	53	0.86	0.630	0.550	7500
Mean		53	0.864	0.560	0.502	67
Standard Deviation		2.098	0.141	0.065	0.049	5.3
250 West	23	58.3	1.200*	0.634	0.592	63
250 West	23.5	56.3	0.72	0.590	0.505	66
250 West	24	55.2	0.84	0.520	0.469	69
250 West	24.5	46.9*	0.950*	0.692	0.560	65
250 West	25	59.5	0.73	0.563	0.470	67
Mean		55.24	0.888	0.600	0.519	66
Standard Deviation		4.95	0.198	0.0661	0.055	2.2

Huron R162 (M1)-2007						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
162East	14.50	62.6	0.570	0.743	0.400	NA
162East	15.00	59.6	0.550	0.684	0.400	NA
162East	15.50	60.3	0.530	0.738	0.400	NA
162East	16.00	60.5	0.750	0.705	0.400	NA
162East	16.50	64.8	0.590	0.747	0.649	NA
162East	17.00	60.7	0.640	0.774	0.685	NA
162East	17.50	61.8	0.540	0.745	0.642	NA
162East	18.00	63.1	0.680	0.760	0.665	NA
162East	18.50	63.4	0.660	0.738	0.655	NA
Mean		61.5	0.612	0.737	0.544	NA
Standard Deviation		2	0.07	0.027	0.029	NA
162West	14.50	62.4	0.690	0.732	0.647	NA
162West	15.00	65.6	0.660	0.683	0.579	NA
162West	15.50	61.9	0.630	0.718	0.595	NA
162West	16.00	62.7	0.570	0.777	0.667	NA
162West	16.50	63.3	0.660	0.740	0.631	NA
162West	17.00	60.3	0.670	0.774	0.655	NA
162West	17.50	62	0.690	0.729	0.607	NA
162West	18.00	53	0.560	0.695	0.545	NA
162West	18.50	57.4	0.630	0.752	0.634	NA
Mean		60.9	0.64	0.733	0.618	NA
Standard Deviation		3.7	0.048	0.032	0.04	NA

Huron R162 (M1)-2008						
Rout	Section	LWST	CTM	DFT		BPT
		SN	MPD	DFT20	DFT64	BPN
162East	14.50	62.649	0.730	0.763	0.651	72.2
162East	15.00	60.471	0.540	0.722	0.620	70
162East	15.50	64.233	0.540	0.770	0.640	71.2
162East	16.00	62.649	0.820	0.719	0.624	68
162East	16.50	63.243	0.640	0.728	0.634	69.2
162East	17.00	63.144	0.600	0.805	0.702	73
162East	17.50	65.421	0.600	0.777	0.665	74.8
162East	18.00	62.748	0.620	0.681	0.599	64.8
162East	18.50	64.233	0.730	0.718	0.647	72.8
Mean		63.2	0.647	0.743	0.642	70.7
Standard Deviation		1.38	0.094	0.038	0.029	3
162West	14.50	68.29	0.630	0.718	0.630	67.4
162West	15.00	64.33	0.770	0.736	0.638	69.2
162West	15.50	65.62	0.570	0.758	0.606	69.2
162West	16.00	65.22	0.640	0.785	0.673	73
162West	16.50	62.75	0.630	0.776	0.670	69.8
162West	17.00	62.75	0.720	0.801	0.664	73.2
162West	17.50	64.63	0.680	0.742	0.603	70.2
162West	18.00	63.84	0.550	0.674	0.542	70.4
162West	18.50	64.23	0.690	0.639	0.531	67.2
Mean		64.63	0.653	0.737	0.617	70
Standard Deviation		1.68	0.07	0.053	0.053	2.1

Huron R162 (M1)-2009						
Rout	Section	LWST	CTM	DFT		BPT
		SN	MPD	DFT20	DFT64	BPN
162East	14.50	62.52	0.660	0.830	0.700	78
162East	15.00	63.653	0.600	0.850	0.730	77
162East	15.50	64.168	0.520	0.870	0.760	76
162East	16.00	66.64	0.570	0.810	0.690	73
162East	16.50	66.743	0.540	0.770	0.660	64
162East	17.00	65	0.600	0.840	0.740	74
162East	17.50	66.434	0.700	0.800	0.700	75
162East	18.00	67.052	0.550	0.760	0.630	68
162East	18.50	66.434	0.700	0.860	0.720	74
Mean		65.4	0.604	0.821	0.703	73.2
Standard Deviation		1.63	0.068	0.039	0.04	4.5
162West	14.50	65.10	0.690	0.840	0.750	72
162West	15.00	69.42	0.770	0.850	0.750	74
162West	15.50	64.40	0.640	0.840	0.720	74
162West	16.00	64.30	0.680	0.840	0.730	74
162West	16.50	68.70	0.750	0.850	0.740	73
162West	17.00	70.04	0.620	0.810	0.690	67
162West	17.50	63.34	0.640	0.720	0.600	66
162West	18.00	63.96	0.440	0.760	0.590	66
162West	18.50	66.85	0.690	0.850	0.710	73
Mean		66.23	0.658	0.818	0.698	71
Standard Deviation		2.57	0.096	0.047	0.06	3.6

Huron R162 (M1)-2010						
Rout	Section	LWST	CTM	DFT		BPT
		SN	MPD	DFT20	DFT64	BPN
162East	14.50	66.3	0.640	0.746	0.660	80
162East	15.00	43.2	0.720	0.760	0.660	76
162East	15.50	64	0.540	0.840	0.730	83
162East	16.00	68.1	0.710	0.820	0.740	80
162East	16.50	62.9	0.560	0.780	0.680	75
162East	17.00	68.3	0.640	0.850	0.750	82
162East	17.50	66.4	0.690	0.770	0.670	77
162East	18.00	62.2	0.790	0.850	0.770	85
162East	18.50	64.3	0.690	0.730	0.660	78
Mean		62.85	0.664	0.794	0.702	76.9
Standard Deviation		7.67	0.078	0.047	0.045	3.4
162West	14.50	66.20	0.820	0.800	0.775	82
162West	15.00	69.70	0.720	0.780	0.700	78
162West	15.50	66.40	0.700	0.760	0.660	73
162West	16.00	65.50	0.740	0.800	0.790	82
162West	16.50	60.20	0.660	0.850	0.740	82
162West	17.00	64.00	0.620	0.820	0.710	78
162West	17.50	67.10	0.640	0.795	0.685	79
162West	18.00	58.50	0.670	0.800	0.740	82
162West	18.50	64.00	0.670	0.830	0.710	80
Mean		64.62	0.693	0.804	0.723	79.6
Standard Deviation		3.47	0.061	0.027	0.042	3

Huron R162 (M1)-2011						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
162East	14.50	62.34	0.650	0.743	0.740	55
162East	15.00	65.15	0.660	0.684	0.720	82
162East	15.50	64.57	0.540	0.738	0.700	80
162East	16.00	60.01	0.780	0.705	0.700	85
162East	16.50	49.53*	0.750	0.747	0.700	84
162East	17.00	64.08	0.850	0.774	0.680	83
162East	17.50	62.53	0.620	0.745	0.680	88
162East	18.00	54.87	0.720	0.760	0.690	87
162East	18.50	65.15	0.780	0.738	0.600	80
Mean		61	0.706	0.737	0.69	80.4
Standard Deviation		5.37	0.096	0.027	0.039	9.9
162West	14.50	63.70	0.870	0.732	0.700	81
162West	15.00	63.60	0.760	0.750	0.740	84
162West	15.50	61.37	0.800	0.718	0.690	84
162West	16.00	64.08	0.710	0.777	0.770	80
162West	16.50	55.94	0.740	0.800	0.770	84
162West	17.00	61.95	0.780	0.774	0.760	87
162West	17.50	63.41	0.790	0.729	0.720	83
162West	18.00	57.88	0.700	0.750	0.770	85
162West	18.50	65.35	0.850	0.752	0.740	85
Mean		61.92	0.778	0.754	0.745	83.7
Standard Deviation		3.1	0.058	0.026	0.031	2.1

Huron R162 (M1)-2012						
Rout	Section	LWST	CTM	DFT		BPT
		SN	MPD	DFT20	DFT64	BPN
162East	14.50	57.00	0.633	0.774	0.723	83.5
162East	15.00	50.00	0.640	0.772	0.735	84.7
162East	15.50	53.00	0.650	0.713	0.683	79.8
162East	16.00	57.00	0.610	0.723	0.709	82.7
162East	16.50	62.00	0.730	0.709	0.674	76.8
162East	17.00	60.00	0.790	0.679	0.593	84.2
162East	17.50	65.00	0.630	0.696	0.568	88.5
162East	18.00	63.00	0.590	0.748	0.652	90.7
162East	18.50	56.00	0.910*	0.468	0.434	83
Mean		58.11	0.687	0.698	0.641	83.8
Standard Deviation		4.86	0.10	0.092	0.096	4.1
162West	14.50	62.00	0.800	0.714	0.700	85.7
162West	15.00	62.00	0.760	0.729	0.719	79.5
162West	15.50	63.00	0.730	0.683	0.710	78.2
162West	16.00	63.00	0.830	0.767	0.657	84.8
162West	16.50	63.00	0.700	0.791	0.754	82.8
162West	17.00	61.00	0.710	0.793	0.786	82.5
162West	17.50	66.00	0.810	0.748	0.691	84.8
162West	18.00	64.00	0.730	0.706	0.650	79
162West	18.50	62.00	0.700	0.714	0.690	80.3
Mean		62.89	0.752	0.74	0.707	82
Standard Deviation		1.45	0.05	0.039	0.043	2.8

Huron R250 (M2)2007						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
250North	3.79	33.86	0.600	0.437	0.377	NA
250North	4.25	38.71	0.580	0.439	0.356	NA
250North	4.65	37.09	0.840	0.397	0.336	NA
Mean		36.55	0.673	0.424	0.356	NA
Standard Deviation		2.47	0.145	0.024	0.021	NA
250South	3.79	34.97	0.660	0.396	0.335	NA
250South	4.27	34.37	0.610	0.417	0.353	NA
250South	4.67	44.26	0.680	0.479	0.407	NA
Mean		37.87	0.65	0.431	0.365	NA
Standard Deviation		5.55	0.036	0.043	0.037	NA

Huron R250 (M2)2008						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
250North	3.79	37.70	0.570	0.413	0.356	44
250North	4.25	39.98	1.010*	0.466	0.421	44.2
250North	4.65	41.86	0.710	0.413	0.363	38.2
Mean		39.85	0.763	0.431	0.38	42.1
Standard Deviation		2.08	0.225	0.031	0.036	3.4
250South	3.79	36.81	0.530	0.414	0.354	41.8
250South	4.27	40.87	0.720	0.419	0.383	43.2
250South	4.67	42.06	0.790	0.463	0.417	40.2
Mean		39.91	0.68	0.432	0.385	41.7
Standard Deviation		2.75	0.135	0.027	0.032	1.5

Huron R250 (M2)2009						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
250North	3.79	37.18	0.610	0.380	0.320	42
250North	4.25	38.52	0.630	0.490	0.420	51
250North	4.65	39.45	0.630	0.380	0.320	50
Mean		38.38	0.623	0.417	0.353	47.7
Standard Deviation		1.14	0.012	0.064	0.058	4.9
250South	3.79	41.20	0.430	0.340	0.285	45
250South	4.27	37.29	0.710	0.410	0.330	42
250South	4.67	42.33	0.690	0.420	0.340	42
Mean		40.27	0.61	0.39	0.318	43
Standard Deviation		2.65	0.156	0.044	0.029	1.7

Huron R250 (M2)2010						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
250North	3.79	41.25	0.600	0.350	0.300	44
250North	4.25	40.67	0.580	0.450	0.360	51
250North	4.65	43.87	0.840	0.400	0.320	47
Mean		41.93	0.673	0.4	0.327	47.3
Standard Deviation		1.71	0.145	0.05	0.031	3.5
250South	3.79	40.38	0.660	0.350	0.280	48
250South	4.27	41.45	0.610	0.440	0.380	49
250South	4.67	42.61	0.680	0.420	0.340	47
Mean		41.48	0.65	0.403	0.333	48
Standard Deviation		1.12	0.036	0.047	0.05	1

Huron R250 (M2)2011						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
250North	3.79	33.60	0.610	0.403	0.470	50
250North	4.25	39.20	0.710	0.410	0.450	54
250North	4.65	38.00	0.470	0.420	0.350	50
Mean		36.93	0.597	0.411	0.423	51.3
Standard Deviation		2.95	0.121	0.009	0.064	2.3
250South	3.79	28.20	0.520	0.375	0.400	50
250South	4.27	34.80	0.900*	0.400	0.450	47
250South	4.67	40.00	0.670	0.470	0.410	51
Mean		34.33	0.697	0.415	0.42	49.3
Standard Deviation		8.54	0.191	0.049	0.026	2.1

Huron R250 (M2)2012						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
250North	3.79	28.300	0.670	0.388	0.37	55
250North	4.25	25.600	0.760	0.387	0.33	53
250North	4.65	33.200	0.730	0.370	0.36	48
Mean		30	0.720	0.382	0.353	52
Standard Deviation		3.85	0.046	0.010	0.021	3.6
250South	3.79	30	0.760	0.338	0.272	46
250South	4.27	30	0.490	0.337	0.308	51
250South	4.67	34.8	0.670	0.423	0.320	50
Mean		31.60	0.640	0.366	0.300	49
Standard Deviation		2.77	0.137	0.049	0.025	2.6

Lucas R64 (M3)-2007						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
64North	9.00	39.486	0.380*	0.730*	0.490	NA
64North	9.50	50.277	0.420	0.531	0.466	NA
64North	10.00	48.792	0.490	0.480	0.421	NA
64North	10.50	49.089	0.590	0.511	0.458	NA
64North	11.00	45.426	0.480	0.479	0.418	NA
64North	11.50	47.406	0.510	0.505	0.457	NA
64North	12.00	46.416	0.460	0.502	0.440	NA
Mean		46.699	0.476	0.534	0.450	NA
Standard Deviation		3.585	0.067	0.088	0.026	NA
64South	9.00	42.357	0.500	0.492	0.442	NA
64South	9.50	47.109	0.560	0.536	0.474	NA
64South	10.00	48.000	0.440	0.463	0.403	NA
64South	10.50	48.297	0.420	0.451	0.400	NA
64South	11.00	46.614	0.510	0.506	0.465	NA
64South	11.50	41.961	0.560	0.434	0.414	NA
64South	12.00	45.228	0.550	0.474	0.417	NA
Mean		45.65	0.506	0.479	0.431	NA
Standard Deviation		2.589	0.057	0.35	0.030	NA

Lucas R64 (M3)-2008						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
64North	9.00	38.592	0.460	0.470	0.282	48
64North	9.50	45.423	0.410	0.424	0.387	56
64North	10.00	49.680	0.600	0.456	0.411	48
64North	10.50	56.709	0.680*	0.548	0.488	52.2
64North	11.00	42.552	0.460	0.474	0.422	50
64North	11.50	48.492	0.460	0.507	0.448	50
64North	12.00	49.284	0.590	0.480	0.433	52
Mean		47.247	0.523	0.480	0.447	50.9
Standard Deviation		5.794	0.100	0.039	0.069	2.8
64South	9.00	42.552	0.590	0.466	0.433	51.2
64South	9.50	50.274	0.590	0.514	0.476	51.8
64South	10.00	48.591	0.510	0.460	0.405	50
64South	10.50	49.977	0.460	0.495	0.434	50.2
64South	11.00	49.482	0.590	0.495	0.439	48.2
64South	11.50	45.324	0.510	0.472	0.433	52.2
64South	12.00	45.324	0.630	0.452	0.406	46.8
Mean		47.361	0.554	0.479	0.432	50.1
Standard Deviation		2.966	0.061	0.023	0.024	2

Lucas R64 (M3)-2009						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
64North	9.00	39.963	0.520	0.430	0.530	48
64North	9.50	46.143	0.510	0.400	0.340	50
64North	10.00	47.173	0.630	0.470	0.420	51
64North	10.50	51.293	0.950*	0.470	0.450	50
64North	11.00	42.126	0.760	0.470	0.430	48
64North	11.50	45.113	0.630	0.570	0.540	48
64North	12.00	47.379	0.630	0.440	0.420	45
Mean		45.599	0.661	0.464	0.447	48.6
Standard Deviation		3.706	0.152	0.053	0.069	2
64South	9.00	43.053	0.730	0.450	0.400	47
64South	9.50	49.851	0.646	0.490	0.460	49
64South	10.00	48.821	0.580	0.420	0.400	50
64South	10.50	49.336	0.630	0.410	0.390	48
64South	11.00	45.010	0.610	0.440	0.410	50
64South	11.50	46.452	0.650	0.440	0.400	44
64South	12.00	46.040	0.860	0.420	0.420	45
Mean		46.938	0.672	0.439	0.411	47.6
Standard Deviation		2.504	0.095	0.027	0.023	2.4

Lucas R64 (M3)-2010						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
64North	9.00	45.500	0.520	0.592	0.791	51
64North	9.50	51.400	0.510	0.406	0.364	50
64North	10.00	46.200	0.640	0.455	0.413	50
64North	10.50	49.300	0.660	0.566	0.501	55
64North	11.00	46.800	0.550	0.437	0.399	43
64North	11.50	46.200	0.650	0.416	0.377	43
64North	12.00	50.500	0.660	0.388	0.347	40
Mean		47.986	0.599	0.466	0.456	47.4
Standard Deviation		2.369	0.069	0.081	0.156	5.4
64South	9.00	49.400	0.780	0.477	0.431	49
64South	9.50	54.500	0.760	0.490	0.474	47
64South	10.00	52.000	0.720	0.499	0.478	42
64South	10.50	55.200	0.730	0.630	0.570	54
64South	11.00	47.600	0.640	0.432	0.407	43
64South	11.50	40.000	0.780	0.484	0.453	44
64South	12.00	42.200	0.550	0.703	0.642	57
Mean		48.700	0.709	0.531	0.494	48
Standard Deviation		5.865	0.085	0.097	0.083	5.7

Lucas R64 (M3)-2011						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
64North	9.00	43.000	0.630	0.366	0.660	50
64North	9.50	43.400	0.460	0.460	0.430	48
64North	10.00	45.100	0.620	0.520	0.490	54
64North	10.50	43.100	0.670	0.450	0.430	55
64North	11.00	42.000	0.560	0.480	0.440	50
64North	11.50	41.000	0.560	0.460	0.430	45
64North	12.00	42.700	0.800	0.390	0.370	46
Mean		42.900	0.614	0.447	0.464	49.7
Standard Deviation		1.265	0.106	0.053	0.093	3.8
64South	9.00	37.000	0.770	0.550	0.540	50
64South	9.50	46.000	0.790	0.560	0.570	44
64South	10.00	45.400	0.910	0.540	0.490	49
64South	10.50	44.200	0.680	0.500	0.480	57
64South	11.00	42.700	0.680	0.490	0.440	50
64South	11.50	42.000	0.990	0.590	0.540	50
64South	12.00	42.400	0.580	0.470	0.430	59
Mean		42.814	0.771	0.529	0.499	51.3
Standard Deviation		2.984	0.142	0.043	0.053	5.1

Lucas R64 (M3)-2012						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
64North	9.00	40.00	0.68	0.30	0.31	44
64North	9.50	44.00	0.60	0.46	0.30	50
64North	10.00	45.00	0.71	0.38	0.36	51
64North	10.50	44.00	0.52	0.36	0.38	53
64North	11.00	44.00	0.75	0.35	0.34	54
64North	11.50	44.00	0.55	0.23	0.23	55
64North	12.00	45.00	0.63	0.34	0.34	54
Mean		43.71	0.63	0.34	0.32	52
Standard Deviation		1.70	0.11	0.07	0.05	3
64South	9.00	45.00	0.66	0.50	0.43	57
64South	9.50	42.90	0.67	0.33	0.33	50
64South	10.00	43.00	0.82	0.35	0.36	50
64South	10.50	50.00	0.64	0.34	0.38	46
64South	11.00	49.70	0.65	0.36	0.30	49
64South	11.50	51.00	0.93	0.35	0.35	44
64South	12.00	42.70	0.65	0.33	0.40	56
Mean		46.33	0.72	0.37	0.36	50
Standard Deviation		3.75	0.11	0.06	0.05	4

Wood County R 22(M4)-2007						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
25North Drive	16	45.62	0.610	0.433	0.418	NA
25North Drive	16.5	47.41	0.560	0.477	0.444	NA
25North Drive	17	42.65	0.600	0.468	0.451	NA
25North Drive	17.5	47.41	0.490	0.470	0.456	NA
25North Drive	18	48.40	0.550	0.496	0.483	NA
25North Drive	18.5	47.60	0.630	0.446	0.434	NA
25North Drive	19	45.13	0.540	0.490	0.486	NA
25North Drive	19.5	43.84	0.690	0.456	0.453	NA
25North Drive	20	45.43	0.530	0.469	0.433	NA
Mean		45.94	0.578	0.467	0.451	NA
Standard Deviation		1.91	0.061	0.020	0.022	NA
25North Pass	16	53.25	0.740	0.608	0.551	NA
25North Pass	16.5	56.81	0.650	0.625	0.580	NA
25North Pass	17	52.36	0.600	0.578	0.534	NA
25North Pass	17.5	53.35	0.620	0.617	0.565	NA
25North Pass	18	54.24	0.660	0.631	0.578	NA
25North Pass	18.5	54.24	0.630	0.595	0.552	NA
25North Pass	19	53.05	0.560	0.625	0.589	NA
25North Pass	19.5	51.27	0.600	0.544	0.529	NA
25North Pass	20	50.45	0.520	0.537	0.512	NA
Mean		53.22	0.620	0.596	0.554	NA
Standard Deviation		1.85	0.063	0.035	0.026	NA

Wood County R 22(M4)-2008						
Rout	Section	LWST	CTM	DFT		BPT
		SN	MPD	DFT20	DFT64	BPN
25North Drive	16	50.00	0.630	0.464	0.442	54.6
25North Drive	16.5	54.00	0.630	0.483	0.463	60.4
25North Drive	17	49.98	0.600	0.466	0.454	53.8
25North Drive	17.5	49.78	0.580	0.487	0.467	57
25North Drive	18	53.94	0.610	0.500	0.467	55
25North Drive	18.5	50.27	0.610	0.446	0.427	52.8
25North Drive	19	56.41	0.700	0.499	0.463	56.8
25North Drive	19.5	51.56	0.690	0.435	0.431	53.2
25North Drive	20	50.97	0.700	0.461	0.438	53.8
Mean		51.88	0.639	0.471	0.450	55.3
Standard Deviation		2.35	0.046	0.023	0.016	2.4
25North Pass	16	60.37	0.690	0.520	0.505	62
25North Pass	16.5	59.28	0.760	0.600	0.550	67
25North Pass	17	59.48	0.590	0.543	0.505	57
25North Pass	17.5	56.31	0.670	0.567	0.539	63
25North Pass	18	59.58	0.590	0.574	0.537	65
25North Pass	18.5	60.57	0.740	0.595	0.570	63
25North Pass	19	57.79	0.650	0.581	0.536	66
25North Pass	19.5	55.02	0.700	0.518	0.504	59
25North Pass	20	48.88	0.550	0.506	0.500	57
Mean		57.48	0.660	0.556	0.527	62.1
Standard Deviation		3.72	0.072	0.035	0.025	3.7

Wood County R 22(M4)-2009						
Rout	Section	LWST	CTM	DFT		BPT
		SN	MPD	DFT20	DFT64	BPN
25North Drive	16	42.54	0.620	0.440	0.430	52
25North Drive	16.5	46.97	0.620	0.480	0.450	54
25North Drive	17	47.38	0.520	0.460	0.423	54
25North Drive	17.5	51.29	0.720	0.450	0.440	53
25North Drive	18	52.32	0.750	0.470	0.430	47
25North Drive	18.5	48.31	0.640	0.460	0.425	55
25North Drive	19	52.32	0.740	0.430	0.410	54
25North Drive	19.5	49.85	0.830	0.404	0.415	55
25North Drive	20	41.41	0.550	0.430	0.420	53
Mean		48.04	0.666	0.447	0.427	53
Standard Deviation		3.98	0.101	0.024	0.012	2.4
25North Pass	16	55.93	0.720	0.517	0.500	50
25North Pass	16.5	59.12	0.670	0.610	0.530	54
25North Pass	17	59.53	0.640	0.510	0.490	60
25North Pass	17.5	59.02	0.720	0.580	0.570	60
25North Pass	18	57.47	0.720	0.539	0.530	54.2
25North Pass	18.5	60.77	0.680	0.550	0.530	56.2
25North Pass	19	59.64	0.710	0.534	0.505	58.8
25North Pass	19.5	51.60	0.750	0.486	0.480	54.2
25North Pass	20	47.17	0.520	0.487	0.480	53.2
Mean		56.69	0.681	0.535	0.513	55.6
Standard Deviation		4.50	0.069	0.041	0.030	3.4

Wood County R 22(M4)-2010						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
25North Drive	16	42.42	0.830	0.420	0.370	45
25North Drive	16.5	44.65	0.810	0.440	0.490	56
25North Drive	17	43.29	0.780	0.440	0.400	52
25North Drive	17.5	44.55	0.750	0.470	0.430	53
25North Drive	18	45.23	0.600	0.430	0.410	53
25North Drive	18.5	44.36	0.740	0.440	0.420	47
25North Drive	19	44.84	0.780	0.440	0.420	47
25North Drive	19.5	43.78	0.840	0.400	0.410	49
25North Drive	20	41.00	0.690	0.410	0.390	49
Mean		43.79	0.758	0.432	0.416	50.1
Standard Deviation		1.36	0.075	0.020	0.033	3.6
25North Pass	16	51.43	0.580	0.540	0.510	54
25North Pass	16.5	59.58	0.770	0.570	0.570	55
25North Pass	17	53.76	0.700	0.520	0.500	52
25North Pass	17.5	56.58	0.740	0.594	0.550	58
25North Pass	18	51.05	0.720	0.520	0.500	54
25North Pass	18.5	54.25	0.880	0.530	0.510	55
25North Pass	19	48.91	0.800	0.510	0.490	57
25North Pass	19.5	44.74	0.760	0.480	0.475	52
25North Pass	20	43.09	0.770	0.430	0.480	47
Mean		51.49	0.747	0.522	0.509	53.8
Standard Deviation		5.33	0.081	0.048	0.031	3.2

Wood County R 22(M4)-2011						
Rout	Section	LWST	CTM	DFT		BPT
		SN	MPD	DFT20	DFT64	BPN
25North Drive	16	41.00	0.870	0.440	0.450	50
25North Drive	16.5	46.24	0.740	0.400	0.500	56
25North Drive	17	43.62	0.750	0.443	0.436	50
25North Drive	17.5	44.20	0.620	0.440	0.500	52
25North Drive	18	47.98	0.750	0.400	0.480	53
25North Drive	18.5	48.18	0.690	0.450	0.460	52
25North Drive	19	46.24	0.810	0.420	0.510	50
25North Drive	19.5	41.77	0.770	0.380	0.450	51
25North Drive	20	40.80	0.630	0.400	0.460	48
Mean		44.45	0.737	0.419	0.410	51.3
Standard Deviation		2.87	0.080	0.025	0.027	2.3
25North Pass	16	49.825	0.790	0.530	0.500	55
25North Pass	16.5	57.1	0.860	0.560	0.560	70
25North Pass	17	55.16	0.770	0.524	0.530	52
25North Pass	17.5	51.959	0.760	0.533	0.530	54
25North Pass	18	51.959	0.680	0.542	0.500	54
25North Pass	18.5	51.765	0.770	0.530	0.530	45
25North Pass	19	50.504	0.810	0.530	0.550	50
25North Pass	19.5	45.848	0.820	0.493	0.500	50
25North Pass	20	45.751	0.630	0.419	0.470	48
Mean		51.10	0.766	0.518	0.519	53.1
Standard Deviation		3.75	0.071	0.041	0.028	7.1

Wood County R 22(M4)-2012						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
25North Drive	16	41.00	0.760	0.382	0.405	51
25North Drive	16.5	44.70	0.870	0.390	0.420	54
25North Drive	17	43.60	0.810	0.403	0.441	50
25North Drive	17.5	45.20	0.790	0.422	0.453	51
25North Drive	18	48.00	0.710	0.301	0.322	54
25North Drive	18.5	46.90	0.820	0.405	0.439	50
25North Drive	19	47.00	0.790	0.435	0.443	50
25North Drive	19.5	43.10	0.890	0.300	0.308	52
25North Drive	20	38.80	0.780	0.375	0.422	49
Mean		44.26	0.802	0.379	0.406	51.2
Standard Deviation		3.00	0.054	0.048	0.054	1.8
25North Pass	16	42	0.720	0.500	0.502	48
25North Pass	16.5	54	0.690	0.555	0.554	50
25North Pass	17	52.7	0.720	0.586	0.563	56
25North Pass	17.5	52	0.730	0.506	0.515	56
25North Pass	18	52	0.730	0.530	0.510	57
25North Pass	18.5	41	0.720	0.539	0.540	50
25North Pass	19	44.2	0.750	0.552	0.540	50
25North Pass	19.5	49.3	0.770	0.452	0.479	51
25North Pass	20	40.3	0.730	0.428	0.432	48
Mean		47.50	0.729	0.516	0.515	51.8
Standard Deviation		5.25	0.022	0.051	0.041	3.6

Wood County R 22(M4)-2007						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
25South Drive	16	46.71	0.590	0.498	0.473	NA
25South Drive	16.5	46.02	0.590	0.483	0.464	NA
25South Drive	17	47.11	0.620	0.488	0.476	NA
25South Drive	17.5	58.10	0.660	0.473	0.468	NA
25South Drive	18	45.33	0.510	0.463	0.431	NA
25South Drive	18.5	46.52	0.520	0.482	0.456	NA
25South Drive	19	42.26	0.630	0.433	0.420	NA
25South Drive	19.5	41.37	0.690	0.419	0.409	NA
25South Drive	20	41.96	0.440	0.405	0.377	NA
Mean		46.15	0.583	0.460	0.442	NA
Standard Deviation		5.00	0.080	0.033	0.022	NA
25South Pass	16	53.54	0.720	0.576	0.560	NA
25South Pass	16.5	57.31	0.590	0.590	0.553	NA
25South Pass	17	58.30	0.540	0.610	0.563	NA
25South Pass	17.5	57.50	0.600	0.600	0.567	NA
25South Pass	18	54.14	0.670	0.536	0.504	NA
25South Pass	18.5	60.57	0.560	0.581	0.541	NA
25South Pass	19	53.25	0.600	0.516	0.495	NA
25South Pass	19.5	49.49	0.480	0.533	0.483	NA
25South Pass	20	49.49	0.500	0.368	0.340	NA
Mean		54.84	0.584	0.546	0.512	NA
Standard Deviation		3.87	0.077	0.074	0.072	NA

Wood County R 22(M4)-2008						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
25South Drive	16	54.33	0.610	0.476	0.466	53.2
25South Drive	16.5	58.10	0.680	0.437	0.423	45.8
25South Drive	17	56.71	0.700	0.468	0.457	52
25South Drive	17.5	58.79	0.670	0.437	0.424	49.2
25South Drive	18	47.50	0.650	0.438	0.419	49
25South Drive	18.5	48.20	0.570	0.459	0.440	51.4
25South Drive	19	46.02	0.690	0.431	0.412	49.8
25South Drive	19.5	48.10	0.690	0.408	0.409	47.2
25South Drive	20	43.54	0.450	0.423	0.402	48.2
Mean		51.25	0.634	0.442	0.428	49.5
Standard Deviation		5.73	0.081	0.022	0.022	2.4
25South Pass	16	64.63	0.710	0.596	0.576	57
25South Pass	16.5	58.99	0.550	0.617	0.570	57.2
25South Pass	17	64.23	0.590	0.626	0.568	60.2
25South Pass	17.5	60.77	0.710	0.617	0.581	61.2
25South Pass	18	58.19	0.610	0.560	0.518	57.2
25South Pass	18.5	64.04	0.630	0.558	0.526	56.2
25South Pass	19	59.68	0.650	0.569	0.524	53.2
25South Pass	19.5	61.26	0.520	0.559	0.503	60
25South Pass	20	46.81	0.520	0.430	0.403	56
Mean		59.84	0.610	0.570	0.530	57.6
Standard Deviation		5.43	0.073	0.059	0.056	2.5

Wood County R 22(M4)-2009						
Rout	Section	LWST	CTM	DFT		BPT
		SN	MPD	DFT20	DFT64	BPN
25South Drive	16	51.81	0.860	0.476	0.462	47
25South Drive	16.5	50.57	0.760	0.456	0.416	40
25South Drive	17	49.95	0.580	0.490	0.457	51
25South Drive	17.5	49.65	0.780	0.505	0.467	50
25South Drive	18	47.17	0.640	0.432	0.399	35
25South Drive	18.5	58.30	0.530	0.510	0.446	50
25South Drive	19	49.54	0.550	0.404	0.367	37
25South Drive	19.5	46.45	0.680	0.406	0.403	39
25South Drive	20	41.71	0.680	0.410	0.370	48
Mean		49.46	0.673	0.454	0.421	44.1
Standard Deviation		4.46	0.111	0.043	0.039	6.3
25South Pass	16	60.77	0.690	0.610	0.560	49
25South Pass	16.5	58.30	0.630	0.740	0.660	60
25South Pass	17	59.53	0.600	0.710	0.630	58
25South Pass	17.5	59.95	0.630	0.600	0.530	49
25South Pass	18	57.68	0.640	0.710	0.630	59
25South Pass	18.5	61.08	0.750	0.590	0.540	52
25South Pass	19	58.50	0.750	0.570	0.520	49
25South Pass	19.5	57.89	0.490	0.520	0.564	52
25South Pass	20	58.19	0.410	0.510	0.440	44
Mean		59.10	0.621	0.618	0.564	52.4
Standard Deviation		1.27	0.112	0.084	0.068	5.5

Wood County R 22(M4)-2010						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
25South Drive	16	46.98	0.790	0.465	0.440	52
25South Drive	16.5	44.65	0.740	0.420	0.400	47
25South Drive	17	44.36	0.740	0.450	0.430	51
25South Drive	17.5	46.78	1.050	0.410	0.410	41
25South Drive	18	41.54	0.730	0.430	0.410	44
25South Drive	18.5	43.39	0.640	0.430	0.410	46
25South Drive	19	38.15	0.750	0.400	0.390	42
25South Drive	19.5	41.45	0.770	0.406	0.405	44
25South Drive	20	37.76	0.500	0.410	0.387	45
Mean		42.78	0.746	0.425	0.409	45.8
Standard Deviation		3.35	0.144	0.022	0.017	3.7
25South Pass	16	55.42	0.810	0.624	0.580	60
25South Pass	16.5	54.45	0.610	0.675	0.610	61
25South Pass	17	53.57	0.680	0.563	0.531	62
25South Pass	17.5	55.22	0.590	0.620	0.540	61
25South Pass	18	55.51	0.900	0.700	0.650	63
25South Pass	18.5	55.71	0.670	0.610	0.560	60
25South Pass	19	50.08	0.970	0.530	0.510	51
25South Pass	19.5	55.32	0.700	0.580	0.510	56
25South Pass	20	46.98	0.630	0.606	0.543	63
Mean		53.58	0.729	0.612	0.559	59.7
Standard Deviation		3.04	0.134	0.053	0.047	3.9

Wood County R 22(M4)-2011						
Rout	Section	LWST	CTM	DFT		BPT
		SN	MPD	DFT20	DFT64	BPN
25South Drive	16	44.00	0.790	0.510	0.480	57
25South Drive	16.5	44.00	0.810	0.450	0.450	52
25South Drive	17	49.00	0.740	0.540	0.520	50
25South Drive	17.5	45.60	1.040	0.490	0.480	53
25South Drive	18	45.80	0.680	0.460	0.440	53
25South Drive	18.5	40.00	0.710	0.490	0.480	55
25South Drive	19	44.00	0.760	0.460	0.441	50
25South Drive	19.5	38.50	0.850	0.490	0.480	58
25South Drive	20	42.00	0.500	0.500	0.460	60
Mean		43.66	0.764	0.488	0.470	54.2
Standard Deviation		3.16	0.144	0.028	0.025	3.5
25South Pass	16	45.00	0.750	0.600	0.590	71
25South Pass	16.5	50.00	0.620	0.660	0.640	70
25South Pass	17	53.00	0.650	0.610	0.590	68
25South Pass	17.5	56.00	0.510	0.620	0.580	71
25South Pass	18	57.00	0.760	0.650	0.630	74
25South Pass	18.5	55.00	0.740	0.590	0.560	60
25South Pass	19	56.00	0.690	0.630	0.640	71
25South Pass	19.5	52.00	0.560	0.570	0.560	60
25South Pass	20	56.00	0.590	0.550	0.520	71
Mean		53.33	0.652	0.609	0.590	68.4
Standard Deviation		3.87	0.089	0.036	0.041	5

Wood County R 22(M4)-2012						
Rout	**Section**	**LWST**	**CTM**	**DFT**		**BPT**
		SN	**MPD**	**DFT20**	**DFT64**	**BPN**
25South Drive	16	40.00	0.670	0.398	0.467	52
25South Drive	16.5	49.00	0.700	0.390	0.472	50
25South Drive	17	47.20	0.630	0.367	0.401	50
25South Drive	17.5	46.00	0.680	0.360	0.41	50
25South Drive	18	47.00	0.670	0.355	0.414	50
25South Drive	18.5	46.00	0.700	0.388	0.474	51
25South Drive	19	43.30	0.630	0.348	0.424	50
25South Drive	19.5	37.40	0.670	0.356	0.401	46
25South Drive	20	38.00	0.680	0.339	0.407	51
Mean		43.77	0.670	0.367	0.430	50
Standard Deviation		4.30	0.025	0.021	0.032	1.7
25South Pass	16	56.00	0.790	0.510	0.57.7	58
25South Pass	16.5	54.00	0.770	0.397	0.465	55
25South Pass	17	52.00	0.810	0.456	0.500	58
25South Pass	17.5	52.00	0.810	0.520	0.510	55
25South Pass	18	56.00	0.870	0.440	0.500	57
25South Pass	18.5	44.00	0.830	0.437	0.500	62
25South Pass	19	40.00	0.790	0.428	0.445	61
25South Pass	19.5	47.00	0.750	0.418	0.475	57
25South Pass	20	40.00	0.610*	0.400	0.416	58
Mean		49.00	0.781	0.445	0.476	57.9
Standard Deviation		6.44	0.073	0.044	0.033	2.4

APPENDIX E.

STATE OF OHIO

DEPARTMENT OF TRANSPORTATION

SUPPLEMENT XXX

POLISHING AND DETERMINING FRICTION NUMBER

OF GYRATORY COMPACTED SPECIMENS

2013

STATE OF OHIO
DEPARTMENT OF TRANSPORTATION

SUPPLEMENT XXX
POLISHING AND DETERMINING FRICTION NUMBER
OF GYRATORY COMPACTED ASHALT SPECIMENS
2013

XXX.01 Scope. This supplement specifies the procedures for using an Ohio Asphalt Polishing Machine (Polisher) to correctly determine:

1. Friction Degradation curve
2. Suitability of asphalt mixtures for pavement skid resistance requirements
3. Predicting actual project pavement friction over expected life.

Ensure the Polisher meets the below requirements.

XXX.02 Ohio Asphalt Polishing Machine Requirements.

The Polisher is a laboratory accelerated polishing device to polish the flat surface of a gyratory compacted asphalt sample using a rotating rubber disc at a constant rotating speed and under constant vertical force. Ensure that the polishing machine meets the following requirements.

1. Hold a gyratory compacted asphalt sample in place while it is being subjected to rotational polishing action on the flat surface of the sample by a rubber disc

2. Accommodate gyratory compacted sample size of 6 inch (15.24 cm) diameter by 6 inch (15.24 cm) height or 6 inch (15.24cm) diameter by 4 inch (10.16 cm) height

3. Maintain flat contact between rubber disc and sample flat surface during the entire duration of polishing action

4. Maintain a constant vertical force of 290 lb (1.29 kN) during polishing

5. Maintain a constant rotational speed of the rubber disc at 30 rpm

6. Maintain constant water flow of 3.38 oz (100 ml) per minute onto the contact interface between sample top surface and bottom surface of rubber disc during polishing

7. Automatic timer to shut off rubber disc rotation at every one hour interval

8. Rubber disc is made of 90 Durometer SBR rubber

XXX.03 Laboratory Test Procedure for Determining Final Friction Number

This section provides a procedure for determining polishing resistance and final friction number of gyratory compacted asphalt samples. The test procedure consists of the following steps. A minimum of two gyratory compacted samples prepared in accordance with the Job Mix Formula (JMF) are required to check for repeatability of test results.

Step 1: Measure initial BPN of the sample flat surface using British Pendulum Tester and record it as BPN_0 at time t_0

Step 2: Subject sample to a total of 8-hour polishing using the Polisher. Polishing action may be temporarily stopped for visual inspection to ensure that flat contact between sample surface and rubber disc surface is maintained.

Step 3: After 8-hour of polishing, measure final BPN of the sample flat surface and record it as BPN_f

Step 4: Repeat Step 1 to Step 3 for the second sample.

Step 5: Compare final friction number BPN_f of the two samples to make sure that the differences between the two samples are within a reasonable range, say, plus or minus 2. If not, another sample needs to be tested.

Step 6: Take average of two BPN_f and convert it into equivalent SN_f using the following equation

$$SN = 0.862 * BPN - 9.690 \tag{1}$$

Step 7: Compare SN_f with the established acceptance criterion SN acceptable = 32

XXX.04 Laboratory Test Procedure for Friction Degradation Curve.

The Friction Degradation Curve is a curve obtained from tests using the Polisher described in the previous section. It is a curve showing the BPN values, measured by British Pendulum Tester in accordance with ASTM E-303-93, versus polishing time at one hour interval until reaching the 8-hour duration. Example Friction Degradation Curve is shown in Figure E-1.

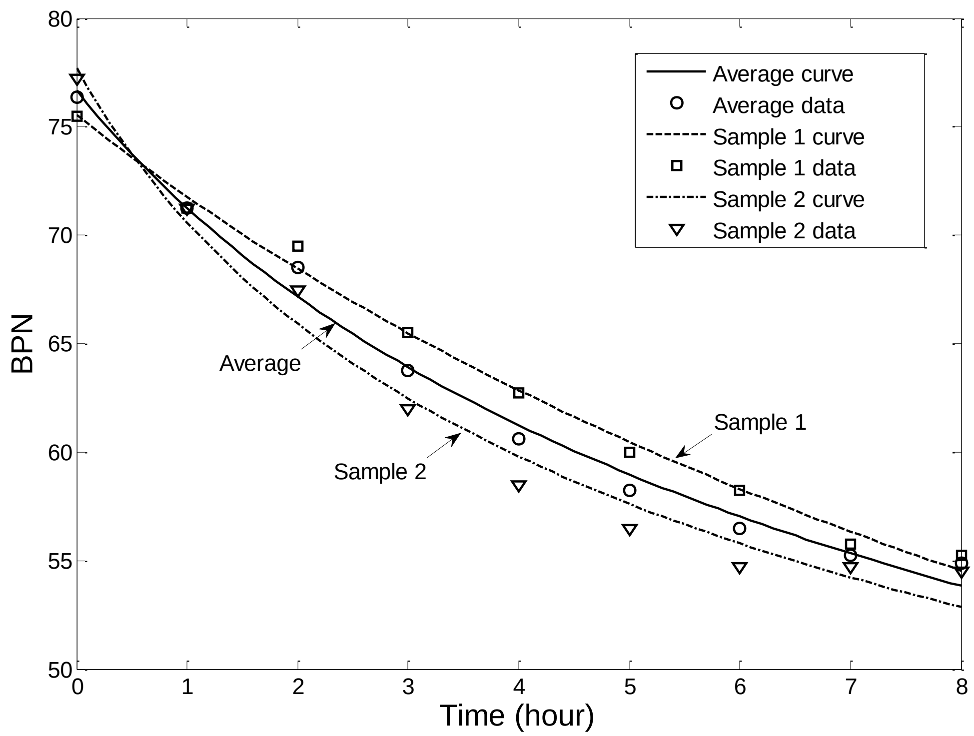


Figure E-1 Example Friction Degradation Curve

Two gyratory compacted samples prepared in accordance with the Job Mix Formula (JMF) are required. The procedure consists of the following steps.

Step 1: Measure initial BPN of the sample flat surface using British Pendulum Tester and record it as BPN_0 at time t_0

Step 2: Subject sample to one hour polishing in the Polisher

Step 3: Measure friction value using British Pendulum Tester and record it as BPN at t, where t indicates accumulated polishing duration

Repeat Step 2 and Step 3 for the next one-hour of polishing and measurement, until a total of 8-hours polishing duration is complete

Plot the Friction Degradation Curve using an average of test results of two samples.

XXX.05 Prediction of Actual Project Pavement Friction Over Expected Life

This section describes the procedure for predicting an actual project pavement friction at the end of the expected project useful life.

1. Calculate fitting parameters to aggregate gradation curve: κ and λ

$$F(x) = 1 - \exp(-(x/\lambda)^{\kappa}) \tag{2}$$

Where x is the sieve size and F(x) is the cumulative percent passing.

An Excel based program is available for performing this task. An example showing input to Excel program and the resulting parameters κ and λ are illustrated herein:

Example: The gradation test data of a pavement material is shown blow:

Sieve Size (in)	Percentage Passing
0.75	100
0.5	100
0.375	98
0.187	62
0.0937	37
0.0469	23
0.0234	15
0.0117	10
0.0059	7
0.0029	4.6

Input the data into the program and the output will be the estimation of the parameters $\kappa = 1.092$ and $\lambda = 0.169$.

2. Compute laboratory friction loss, PV, from Friction Degradation Curve as follows

$$PV = \frac{BPN_o - BPN_8}{BPN_o} * 100 \quad (3)$$

In which,

BPN_o = British Pendulum Friction Number before Polishing

BPN_8 = British Pendulum Friction Number after 8hr Polishing

3. Obtain ADT (Average Daily Traffic) for the project pavement section

4. Use Equation (4) and Equation (5) to compute two index values: time index t_0 and scale index m

Time index:

$$t_0 = -6.366 * 10^{-4} ADT + 0.2874 PV - 185.632\kappa + 1167.8\lambda \quad (4)$$

Scale index:

$$m = -9.2196 * 10^{-5} ADT + 0.0372 PV - 2.3262\kappa + 10.9279\,\lambda \quad (5)$$

5. Select a required service life of the pavement surface in years, denoted as t_{req}

6. Use Equation (1) to convert initial BPN_0 reading in the Friction Degradation Curve into equivalent SN_0

7. Calculate the predicted SN at the selected $t = t_{req}$ using Equation (6)

$$SN = SN_0 (1 + \frac{t}{t_0})^m \quad (6)$$

where SN is the predicted skid number at the end of the expected useful life.