**QUANTIFICATION OF PAVEMENT TEXTURAL AND
FRICTIONAL CHARACTERISTICS USING DIGITAL IMAGE
ANALYSIS**

A thesis submitted to
the Faculty of Graduate Studies and Research
in Partial Fulfillment of the requirements for the degree

Doctor of Philosophy

by

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ABSTRACT

Despite a wealth of research and development concerning pavement surface characteristics, there still exists a need for high volume friction and texture measurement at low cost and the ability to optimize frictional properties at the mix design stage. A rapid, low cost, portable data acquisition and analysis system based upon digital imaging techniques, referred to as the Pavement Surface Imager, was developed during this investigation to assess and predict pavement frictional and textural properties in both rural and urban environments, as well as laboratory testing for forensic analysis and mix design optimization.

To support this development effort, a selection of newly constructed pavements representing different asphalt mixtures was tested in the laboratory with the Pavement Surface Imager, British Pendulum Test and sand patch test, as well as in the field using Carleton University's friction trailer and laser texture sensor. Replicate testing was completed at various levels of polishing to observe the change in friction with time in service.

With this comprehensive database, new relationships have been developed to allow designers to optimize macrotexture and friction at the mix design stage, thereby promoting safety and reducing cost. In its current form, the Pavement Surface Imager is able to directly estimate Mean Texture Depth (MTD) of pavement surfaces and thus avoid the use of the time consuming sand patch test. The ability to assess pavement surface segregation with the Pavement Surface Imager has also been observed.

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CHAPTER 1: INTRODUCTION

1.1 Chapter Objective

The main objective of Chapter 1 is to convince the reader of the merit and importance of the investigation and resulting thesis. This is accomplished by reviewing the importance of the road network in Canada, and how friction and texture contribute to the safety of millions of motorists each year.

The need for the current investigation is highlighted through a review of existing deficiencies and/or gaps in traditional practices related to pavement friction and texture. Built upon this review, a research problem statement and objectives were developed and presented.

Most importantly, the contribution to the existing state of knowledge is discussed to ensure that the research community and pavement engineering industry derive the maximum benefit from the investigation.

Finally, the organization of the thesis is presented for clarity and rapid review.

1.2 Importance of Canada's Road Network

In August 2002, the Provincial and Territorial Ministers Responsible for Transportation and Highway Safety released a document entitled "Partnering for the Future – A Transportation Vision for Canada" with the goal of improving Canada's transportation system in the 21st century [PTMRTS 2002]. The importance of Canada's road network may be directly and immediately observed from the opening paragraph of this document.

Much of what we value, our jobs, our health, our education, our leisure time, are all impacted by the quality and availability of transportation. Every day, people across Canada rely on our transportation system to go to work, to school and a host of other

destinations. And our businesses rely on this same system to move goods from farms, mines, forests and the sea to processing plants and consumers. Transportation is an important part of the everyday lives of all Canadians... [PTMRTHS 2002]

A number of challenges facing the transportation industry are discussed, including globalization, infrastructure renewal, mobility, access and safety, sustainability and effective decision-making. As will be discussed in the following sections, the issue of highway safety remains a key element for the delivery of a modern road transportation system.

1.3 Highway Safety is Paramount

Safety is an overarching consideration in all aspects of the transportation sector. Although there is much work to be done in terms of promoting a culture of safety amongst all users of the roadway, governments must make the necessary investments to modernize our aging infrastructure, thereby enhancing safety [PTMRTHS 2002].

According to Transport Canada [2003], both the number of annual fatalities, as well as the rate of fatalities (fatalities per 10000 vehicles) has steadily declined over the past 20 years. However, a total of 2778 people were killed and almost 223,000 people were injured in vehicle accidents on Canadian highways in 2003 alone. Between 1984 and 2003, a total of 70,126 people have died and over 4.9 million people have been injured as a result of vehicle collisions in Canada. Clearly there is room for additional improvement.

Although more fatal collisions occurred in rural areas than urban centres in 2003 (1539 vs. 936, respectively), many more collisions involving personal injury were experienced in urban centres (110,511 vs. 41,639) [Transport Canada 2003]. The lower average traffic speed within

urban centres is likely the reason for reduced fatalities, however, the increased traffic congestion would explain the large number of total collisions.

The causes of traffic accidents may be classified into three main groups; human factors, the road and its surrounding environment, and the vehicle itself. The pavement engineer is most interested in the road and its surrounding environment. The geometric design (alignment, curves, crests and valleys, etc.) of the road plays an important role toward highway safety. Curves must be designed with sufficient radius and superelevation to accommodate the design traffic speed to avoid run-off-the-road accidents. Crests and valleys must be designed with the proper sight distance to allow motorists sufficient time to observe hazards (stopped cars, animals, etc.) and react accordingly. Of particular interest to this investigation is the provision of a safe, skid resistant pavement surface to allow the acceleration, braking and turning movements required for normal driving operations and minimize slippage during poor weather.

1.4 Friction is the Key

Although up to 90 percent of traffic accidents are due to human factors, the road authority must ensure that the road and its surrounding environment are designed to promote safer driving and accommodate minor driving mistakes. One important aspect of the road environment concerns the frictional properties of the pavement surface-vehicle tire interface.

A pavement becomes slippery when the prevailing conditions are such that lubrication exists between the tire-road surface contact area, or polished away by traffic and/or when vehicle speeds are high enough to hydrodynamically reduce the tire-surface contact below the level required for necessary vehicle manoeuvres [Krummer and Meyer 1967].

1.4.1 The Law of Interaction

“For every action, there is an equal and opposite reaction”

Newton’s Third Law, often referred to as the Law of Interaction, describes an important property of forces – they always occur in pairs, equal in magnitude, but opposite in direction.

To accelerate horizontally, a vehicle’s engine must apply a force to the pavement surface through the tires and the pavement surface must in turn apply a reactive force to the tire to propel it forward. The reason that the pavement is able to provide the reactive force is due to a frictional force at the interface between the pavement and the tire. Perhaps more critical is the ability of the automobile to reduce speed (i.e. brake) or change direction, which are also possible because of frictional forces.

Friction of the tire-pavement interface is therefore critical for acceleration, directional changes and braking of automobiles. As the friction of pavement surfaces decreases due to presence of moisture, ice or wear under traffic loading and other contaminants, the risk of accidents greatly increases. Therefore, the provision of high friction surfaces that can maintain acceptable friction under adverse climatic conditions and resist polishing under traffic loading is an important objective for transportation agencies.

1.4.2 Friction Testing in the Laboratory and Field

Dearinger and Hutchinson [1970] stated that “in simplistic terms, it may be said that most automobile accidents involving skidding are simply due to the unfortunate, but common, combination of a wet pavement and an attempt by the driver to perform a manoeuvre such as braking, cornering or accelerating at a speed too high for the conditions.” That being said, the details of the slipperiness-skid resistance problem are indeed quite complex. At the time of this writing, there are 28 separate (and active) ASTM International standards and guides concerning the measurement of pavement surface skid resistance, aggregate polishing and tire traction as

listed in Table 1.1. The large number of active standards illustrates the importance of skid resistance testing, however, it also suggests that testing practices and equipment have been developed over time without a consistent or common methodology.

1.5 Need for New Research

1.5.1 Overview

Numerous studies of pavement frictional properties have been conducted in the past. A recent literature search on the Transportation Research Information System (TRIS) maintained by the United States Bureau of Transportation Statistics yielded 1993 individual research reports with the key phrase “skid resistance.” Yet much remains to be investigated. The following sections outline the primary needs for the additional research proposed in this document.

1.5.2 Need for Objective Characterization of Pavement Skid Resistance

Current testing devices only provide a relative measurement of pavement frictional properties at a given time. For example, the term “skid resistance,” which is often used interchangeably with pavement “friction,” in fact represents measurement of surface characteristics under a very specific set of circumstances – that being the sliding of a locked wheel on a wet pavement surface (ASTM E274). There are many other methods and conditions under which to measure “friction” and these measurements are always connected to the specific measuring device and operating conditions. At this time, there exists no pavement surface evaluation system that may be used as a basis for fundamental modeling of frictional properties under various combinations of moisture (including ice), temperature, and contamination.

Table 1.1: ASTM Standards Related to Pavement Skid Resistance Testing

ASTM Standard No.	Title
D3319-00	Standard Practice for Accelerated Polishing of Aggregates Using the British Wheel
E274-97	Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire
E303-93 (1998)	Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester
E445/E445M-88 (2001)	Standard Test Method for Stopping Distance on Paved Surfaces Using a Passenger Vehicle Equipped with Full-Scale Tires
E501-94 (2000)	Standard Specification for Standard Rib Tire for Pavement Skid Resistance Tests
E503/E503M-88 (2000)	Standard Test Methods for Measurement of Skid Resistance on Paved Surfaces Using a Passenger Vehicle Diagonal Braking Technique
E524-88 (2000)	Standard Specification for Standard Smooth Tire for Pavement Skid Resistance Tests
E660-90(1996)	Standard Practice for Accelerated Polishing of Aggregates or Pavement Surfaces Using a Small-Wheel, Circular Track Polishing Machine
E670-94(2000)	Standard Test for Side Force Friction on Paved Surfaces Using the Mu-Meter
E707-90(2002)	Standard Test Method for Skid Resistance Measurements Using the North Carolina State University Variable-Speed Friction Tester
E965-96(2001)	Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique
E1337-90(2002)	Standard Test Method for Determining Longitudinal Peak Braking Coefficient of Paved Surfaces Using a Standard Reference Test Tire
E1551-93a(1998)	Standard Specification for Special Purpose, Smooth-Tread Tire, Operated on Fixed Braking Slip Continuous Friction Measuring Equipment
E1844-96	Standard Specification for A Size 10x4-5 Smooth-Tread Friction Test Tire
E1845-01	Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth
E1859-97(2001)	Standard Test Method for Friction Coefficient Measurements Between Tire and Pavement Using a Variable Slip Technique
E1890-01	Standard Guide for Validating New Area Reference Skid Measurement Systems and Equipment
E1911-98	Standard Test Method for Measuring Paved Surface Frictional Properties Using the Dynamic Friction Tester
E1960-98	Standard Practice for Calculating International Friction Index of a Pavement Surface
E2100-02	Standard Practice for Calculating International Runway Friction Index
E2101-00	Standard Test Method for Measuring the Frictional Properties of Winter Contaminated Pavement Surfaces Using an Averaging-Type Spot Measuring Decelerometer
F403-98	Standard Test Method for Tires for Wet Driving Traction in Straight-Ahead Braking, Using Highway Vehicles
F408-99	Standard Test Method for Tires for Wet Traction in Straight-Ahead Braking, Using a Towed Trailer
F424-98	Standard Test Method for Tires for Wet Driving Traction in Straight-Ahead Motion Using Highway Vehicles
F1649-96e1	Standard Test Methods for Evaluating Wet Braking Traction Performance of Passenger Car Tires on Vehicles Equipped with Anti-Lock Braking Systems
F1650-98	Standard Practice for Evaluating Tire Traction Performance Data Under Varying test Conditions
F1805-00	Standard Test Method for Single Wheel Driving Traction in a Straight Line on Snow and Ice Covered Surfaces
G115-98	Standard Guide for Measuring and Reporting Friction Coefficients
G163-99	Standard Guide for Digital Data Acquisition in Wear and Friction Measurements

It should be noted that the World Road Association (formerly the Permanent International Association of Road Congresses – PIARC) conducted an international effort to harmonize pavement friction and texture measurements in 1992, such that measurements from the various devices could be compared [PIARC 1995]. The resulting International Friction Index (IFI) was a step in the right direction, yet it only compares the results of the various (subjective) measures, it does not provide a fundamental or objective measure of friction, nor can it be used to predict pavement friction under different environmental conditions or mix properties.

1.5.3 Need for Safe, Low Cost and High-Volume Skid Resistance Testing

Current pavement friction test methods may be broadly classified as either high-speed devices or manual devices. A further distinction may be made between texture measurement tests and skid resistance tests. High-speed skid resistance devices include the ASTM locked-wheel friction trailer, Saab Friction Tester, Sideways Force Coefficient Routine Investigation Machine (SCRIM), Norsemeter and others. Manual skid resistance devices include the British Pendulum Test (BPT) and Swedish Portable Friction Tester. Manual texture tests include the sand patch test, grease test, outflow meter and others. High-speed texture analysis has also recently become available using lasers, although these systems cannot capture pavement microtexture at this time.

Although high-speed devices provide a safe operating environment and are suitable for high volume network level friction measurement, they are very expensive (up to \$400,000 CAN), and generally cannot be used in an urban setting due to low and/or inconsistent traffic speeds, as well as other geometric design constraints such as curves and intersections. Such devices have not only high capital cost, but also high maintenance and operation costs due to their need for frequent calibration and replacement of wear parts such as specialized test tires.

Manual devices are much lower in cost and are better suited for urban friction measurement. However, these devices are unsuitable for high volume data collection and require the closure of one or more lanes of traffic, thus increasing congestion, safety risk to the operators, as well as high data collection costs. Therefore, the development of a low-cost, high volume evaluation system for both the urban and rural environments with minimal operating costs would be of great interest to road agencies.

1.5.4 Need to Optimize Skid Resistance at Mix Design Stage

With the exception of specialty surfacing mixes, asphalt and concrete pavement mixes are generally not designed for skid resistance, but for resistance to fatigue damage and deformation under traffic loading, as well as environmental damage. Indeed, skid resistance is generally assumed during the mix design stage and is often not assessed until a problem exists in the field.

Instead of this reactive process, there is a need to assess and optimize skid resistance at the mix design stage. By adjusting the mix parameters and materials at the design stage, only incremental additional cost is incurred and the resulting mix may provide considerably enhanced friction performance.

1.6 Research Problem Statement and Objectives

Based on the needs identified in Section 1.5, the two primary goals of the research were:

- 1) Conduct a comprehensive evaluation of image analysis techniques to determine which best quantify pavement surface features that contribute to frictional characteristics, and
- 2) Based on Goal #1, develop a rapid, low cost, portable data acquisition and analysis system based upon digital imaging techniques to objectively assess pavement

frictional properties in both rural and urban environments, as well as for laboratory forensic testing and mix design optimization.

The following research objectives were identified toward achieving these goals:

- a) If possible, re-classify a selection of original Schonfeld (hardcopy) stereophotos using digital photogrammetry software and examine any differences between manual and digital analysis,
- b) Conduct further analysis of the scanned Schonfeld stereophotos both in two and three dimensions to determine which analysis technique(s) best characterizes pavement surface friction characteristics,
- c) Design, construct and calibrate a new digital skid resistance imaging device,
- d) Use the newly developed device, the British Pendulum and sand patch, as well as Carleton University's Saab Friction Trailer and laser texture sensor, to conduct a laboratory and field experiment to examine the change in pavement skid resistance between changes in different mix types, different levels of polishing, surface temperature, and the surfaces resulting from gyratory and field compaction.
- e) Provide conclusions and suggest areas for future research.

1.7 Summary of Anticipated Contribution to Existing Knowledge

Recognizing that the research should be novel and contribute to the existing state of knowledge, this section provides a summary of the major contributions expected from this investigation.

First, by comparing the specimen surfaces produced in the Superpave™ gyratory compactor to as-constructed field surfaces, pavement engineers and mix designers will be able to complete friction and texture testing in the laboratory in a safe and controlled environment while having the ability to estimate field performance. In addition, the ability to estimate friction and texture based on mix properties will allow mix designers to optimize friction and texture in the laboratory without the need for costly trial sections or exposing technical staff to the hazards associated with field testing.

Second, this investigation will result in the development of an inexpensive, rapid, and portable digital imaging system that may be used both in the laboratory and field for documenting pavement surfaces. The images collected will provide immediate characterization of surface friction and texture (as discussed below), as well as provide an archive for future analysis – a feature not provided by other test methods.

Finally, it is hoped that novel application of digital image analysis techniques will replace one or more of the existing tests such as the sand patch test or British Pendulum Test, which are not only time consuming and costly but expose field personnel to traffic closures and their associated hazards.

1.8 Organization and Scope of Thesis

1.8.1 Introduction (Chapter 1)

The introductory chapter provides an overview of the importance of Canada's road network and how roadbuilding agencies should promote highway safety by providing safe, skid resistant pavement surfaces. The need for additional research in this area is provided, as well as

the overall research problem statement and objectives. The contribution of this research to the existing knowledge base is outlined, as well as the organization of the thesis.

1.8.2 Literature Review (Chapter 2)

A considerable amount of literature on the issue of pavement skid resistance exists, however, only a selection was appropriate for this investigation. The literature review is provided in Chapter 2 to discuss the theory behind surface friction, present existing surface classification systems and devices available for skid resistance measurement (and their respective deficiencies), as well as review the numerous factors that affect skid resistance of pavements.

1.8.3 Digital Analysis of Rough Surfaces (Chapter 3)

The use of digital image analysis for surface evaluation has not yet become widespread in the field of civil engineering – particularly the pavement engineering branch. As such, Chapter 3 is included as an introduction to the various 2-dimensional (2D) and 3-dimensional (3D) image analysis techniques available with discussion as to how these techniques can potentially be used to more accurately and cost effectively characterize pavement surface friction characteristics as compared to conventional friction testing devices.

1.8.4 Digital Analysis of Schonfeld Stereographs (Chapter 4)

In the 1970's, a close-range stereographic analysis procedure was developed by Robert Schonfeld of the Ontario Ministry of Transportation. The procedure involved the collection of hardcopy stereographic photos of a pavement surface and then manual analysis by a trained operator to relate the pavement texture – as characterized by a series of parameters – to skid number (SN), as measured by a locked wheel friction tester.

While the correlation between the Schonfeld method and SN values was excellent, the method was very time consuming. Chapter 4 describes an effort to re-analyze a set of stereo images taken by Schonfeld that were scanned to allow modern digital image analysis. Results

from this effort were used to develop the new digital imaging device, as well as guide the analysis program.

1.8.5 Development of the Pavement Surface Imager (Chapter 5)

A new test device, referred to as the Pavement Surface Imager, was developed to collect digital images of pavement surfaces using a multi-image lighting and acquisition technique. The Mark I unit was constructed to collect four images for analysis using the photometric stereo method (PSM). Unfortunately, while the resulting images were suitable for 2D analysis, extraction of a 3D digital elevation model (DEM) did not currently prove feasible using the PSM.

After additional research, a Mark II unit was constructed to collect ten images for analysis using Polynomial Texture Mapping (PTM). PTM provides the normal vectors of the pavement surfaces, although again at this time the extraction of a DEM was not possible due to limitations of current integration techniques.

1.8.6 Research Data Set (Chapter 6)

Eight different paving projects were selected from the 2004 City of Ottawa rehabilitation program for this investigation. A total of nine hot mix asphalt mixes and one microsurfacing mix were sampled for evaluation. Field testing of these projects immediately after construction involved friction testing with Carleton University's Saab Friction Trailer and macrotexture evaluation with a laser texture sensor, as well as collection of core specimens. Replicate field friction testing was completed with time to evaluate the change in friction with traffic volume.

Laboratory sample preparation and testing included the following:

- i) Standard quality assurance (QA) testing for mix properties such as gradation, air voids, asphalt cement content, etc.,
- ii) Recompaction of loose mix in the gyratory compactor,

- iii) Friction testing of the core and gyratory specimens with the British Pendulum,
- iv) Macrotexture evaluation using the Sand Patch Test, and
- v) Imaging with the Pavement Surface Imager.

Replicate British Pendulum testing and imaging were conducted at increasing levels of polishing to evaluate the change in friction with simulated wear. Replicate imaging was completed at different temperatures with the Mark I unit to determine if the surface texture was altered by temperature.

1.8.7 Data Analysis and Results (Chapter 7)

A comprehensive data analysis program was then undertaken. First, a series of new relationships were developed to predict initial friction and macrotexture using mix properties. These new relationships will allow designers to better understand the properties that contribute most to friction and texture and optimize them at the mix design stage.

Second, a series of statistical comparisons were completed to confirm that laboratory prepared specimens from the gyratory compactor may be used to predict field texture and friction; thereby avoiding expensive, time consuming and risky field testing. The benefit of reducing or eliminating the need for personnel to complete testing in the field cannot be overemphasized given the safety hazards involved.

Finally, a great amount of effort was put toward image analysis and relating the resulting parameters to macrotexture and friction. As proposed, numerous two dimensional image analyses were completed to determine whether sufficient accuracy could be obtained without the need for more computationally intense three dimensional techniques.

The research also went beyond the initial proposal by investigating the use of surface normal vectors (a quasi-three-dimensional approach) for measuring friction and texture, which

was highly successful in measuring macrotexture and segregation of the pavement surface. This extremely important result indicates that (with additional testing) it is possible to replace the sand patch test with the Mark II Pavement Surface Imager.

Finally, the considerable database generated during this investigation is available for future analyses using new and/or different techniques.

1.8.8 Conclusions and Recommendations (Chapter 8)

Chapter 8 summarizes the research findings, presents the numerous conclusions made during this investigation, and reinforces the substantial contribution that the research has made to the existing knowledge base concerning pavement friction and texture. A series of recommendations are also provided for future research and consideration.

CHAPTER 2: LITERATURE REVIEW

2.1 Chapter Objective

The main objective of Chapter 2 is to determine the existing deficiencies/gaps in traditional practices related to pavement friction and texture through a comprehensive review of the literature. This information was then used to develop the research goals and objectives for this investigation.

2.2 Fundamentals of Pavement Friction

2.2.1 Overview

It may be readily stated that the issue of pavement friction is complex and dependent upon a great number of variables. Schonfeld [1970] eloquently discusses the issue as follows:

The standard skid-number of a pavement which would make possible to relate the measured skid resistance of one pavement to that of another has so far eluded us. It is possible to question if the concept of the standard skid number is realistic, or whether it is erroneous to conceive of one-skid number as a distinct measurable quantity of something as complex as two hundred square feet of pavement surface.

Furthermore, many of the procedures used to characterize friction measure only a single attribute such as texture depth, mean hydraulic radius, or drainage characteristics. This is why the correlation of skid resistance with texture measurements is often imperfect [Balmer 1978]. Instead, the true pavement frictional properties are determined by all textural features acting in concert [Schonfeld 1970].

The following section provides an introduction to the formation and shape of individual surfaces. When rough surfaces are brought together, it is clearly important to know the

topography of the contacting area [Thomas 1999]. A brief overview of the concepts of contact mechanics are texture interaction with regard to pavement-tire interaction are then also presented.

2.2.2 The Shape of Solid Surfaces

It is well accepted that the shape of surfaces strongly influences the manner in which they interact. However, there remains some confusion as to which textural features play critical roles and which are irrelevant. Therefore, before considering the various techniques of surface analysis, it is useful to provide a background by developing a simply physical picture of the surface of a solid [Thomas 1982].

The surfaces found in modern engineering are generated through a great variety of formative processes. Some may be left with the texture imparted through the major operation that formed the shape such as milling, rolling, extruding and casting. Asphalt pavement surface texture would qualify under this group, as the mix is extruded through the paver and then rolled using compaction devices.

Many other surfaces are subjected to further treatment, particularly when intended for contact with other surfaces. Such treatments include the addition of materials through plating, spraying, painting or other surface coating, as well as the removal of material through grinding, etching or peening. Concrete pavement surfaces would fit into this second group, as the formed or extruded surface is subjected to further texturing, typically tining to provide shallow channels for drainage and improved friction. Some asphalt pavements could also fall into the second group if subjected to additional texturing through the addition of a surface treatment or microsurfacing, or by precision milling to remove bumps that have resulted from the original construction.

The formative processes may be further divided into two classes – those in which many events occur in every small region, and those which interact only once with every part of the

surface [Thomas 1982]. With regard to pavement materials, asphalt pavement surfaces are constructed as single event processes (through a limited number of passes with compaction equipment) whereas concrete pavement surfaces are formed with multi-event processes. With multi-event processes, the final shape of the surface is the cumulative result of all the texturing events applied to it. If these texturing events are applied randomly over the surface and the final shape is the cumulative result of the texturing events, the distribution of heights along the surface profile will tend to follow the normal distribution as the number of events becomes large. Such surfaces are referred to as Gaussian surfaces. With concrete pavements, the timing depth and spacing are relatively constant (by design), thus the distribution of heights will not be Gaussian. Despite the construction techniques for asphalt pavements, the resulting distribution of heights may in fact be Gaussian, as the surface profile is also greatly affected by the aggregate gradation of the mix.

The height distribution of a surface may be evaluated by sampling a profile and developing a cumulative density function (CDF) graph representing the fraction of the surface below an increasing height as shown in Figure 2.1. Surfaces with height distributions that follow the normal distribution will appear as S-shaped with a central range of relatively constant slope (ie. a straight line), whereas non-Gaussian surfaces will appear more non-linear. From the graph, the root-mean square of the deviation of the surface from the nominal surface, Rq , may be readily determined from the slope of the resulting line [Thomas 1982]. The Rq measure represents the roughness of the surface that will be primarily in contact with an opposing surface.

It is important to remember that, for many practical situations, the tribological (i.e. frictional) behaviour depends essentially on the upper most strata of the contacting surfaces and less so (if at all) upon their shape below the centreline [Thomas 1982]. For example, when surfaces of equal roughness touch, the contact regions typically occur in the upper most quartile

(25%) of each surface. Therefore, the fact that some textures may not be described through simple mathematical (i.e. normal) distribution may not be problematic so long as the shape of its upper strata can be determined.

Figure 2.1: Cumulative Height Distributions of Various Surfaces
[Thomas 1982]

In the case of pavements, the roughness of the pavement surface (asphalt or concrete) is similar in magnitude as the depth of tread in a vehicle tire. Thus it is likely that the interaction between the two surfaces will be limited to the upper portion of their respective textures. However, the lower strata of the pavement surface texture will be critical when considering drainage characteristics and tolerance to debris such as sand and salt particles.

The different CDF shapes illustrated in Figure 2.1 suggest that different textures result from different formative processes. Whereas “pure” textures – i.e. those resulting where every single part of the surface has been created through the same process - are rare in engineering, most surfaces have mixed textures indicating that additional formative processes have been applied.

In some cases, subsequent processes may generate new features over the entire surface such that all regions display the marks of all treatments and the final texture is homogeneous. Alternatively, only certain strata may be affected such that the valleys reflect one process while the hills reflect the subsequent treatments. These “stratified” surfaces are of particular interest in engineering, for they offer the opportunity to obtain special combinations of tribological properties that cannot be obtained with a single surface treatment [Thomas 1982]. In terms of public safety, subsequent treatments to increase pavement friction may be considered desirable.

An example of a stratified surface is illustrated in Figure 2.2 where a specimen has been pressed against a harder, smoother surface (such as with stamping). As shown, there are two distinct texture features. The valleys have retained their original shape as imparted through the original formative process, whereas the hills have become smoother as a result of the stamping process. The resulting frictional properties of the surface will be dependent upon either or both of these textures. The lack of hills will allow the surface to slide relatively freely over a second smooth surface, however, the valleys will allow it to retain a lubricant under thin film conditions (a desirable combination for metal engine parts, etc.).

2.2.3 Contact Mechanics of the Vehicle-Tire Interaction

A fundamental observation concerning the interaction of two surfaces when brought together is that the real contact area is independent of the nominal contact area and, in most practical situations, only a tiny fraction of the nominal contact area [Bowden and Tabor 1950].

Figure 2.2: Cumulative Height Distribution of Pressed Surface
[Thomas 1982]

To explain this observation, consider the intersection of a rough surface with a smooth plane parallel to the mean height of the rough surface (i.e the height of a rough surface where the sum of the depths of the valleys is equal to the sum of the heights of the peaks). This case is physically equivalent to an abrasive process that has reduced the peaks of the rough surface above the mean height such that the smooth plane lies flat on the remaining valleys [Thomas 1999]. The fractional area of contact at any height from the mean plane of the rough surface is referred to as the “bearing area,” which is the complement of the cumulative probability

distribution function (CDF) of the profile elevations. For example, if the two surfaces are in contact at the CDF percentage of 75%, the contact area between the surfaces is 25%. Given that the contact regions typically occur in the upper most quartile (25%) of each surface, a real contact area of 25% is common.

While the contact area of rough surfaces can be modelled as a continuum, the behaviour of the surfaces themselves during contact must be modelled as an array of discrete physical objects (asperities) that are distributed in some way both in the plane of the surface – often referred to globally as “texture” where it may be characterized by some kind of wavelength, as well as at right angles to the surface - where it can be characterized by some kind of height or elevation [Thomas 1982, 1999].

A pavement surface may be further described in terms of roughness at different scales. Various scales of roughness affect different aspects of the interaction between the pavement surface and a vehicle tire. As shown in Table 2.1, these ranges in pavement surface roughness are responsible for many different phenomena including skid resistance, rolling resistance, road noise and ride quality.

It is commonly accepted in the literature that frictional forces between a tire and a pavement surface are derived from 2 distinct mechanisms arising from contact between the tire and the pavement surface asperities. The first mechanism is referred to as *adhesion* and involves the penetration of millions of microscopic projections located on the surface of individual aggregate particles into the tire material (Figure 2.3a). The microscopic projections are referred to as *microtexture*. The second mechanism, referred to as tire *hysteresis*, occurs as the tire surface deforms around individual irregularities in the surface (Figure 2.3b) produced by the size, spacing and arrangement of the aggregate particles – referred to as *macrotexture*.

Table 2.1: Ranges of Road Surface Roughness
[Sandberg 1997 with permission from Author]

	Texture Wavelength Range	Peak-to-Peak Amplitude
Microtexture	< 0.5 mm	1 to 500 μm
Macrotexture	0.5 to 50 mm	0.1 to 20 mm
Megatexture	50 to 500 mm	0.1 to 50 mm
Unevenness	0.5 to 50 m	n/a

Figure 2.3: Mechanisms of Tire-Road Friction
[adapted from Oliver 1982 with permission from ARRB Group Ltd.]

Extensive research in the laboratory and field has shown that macrotexture is more important for large-scale drainage of surface water, while microtexture is more important for penetrating thin water films and providing contact between the pavement surface and vehicle tire.

2.2.4 Interaction of Microtexture and Macrotexture

The influence of microtexture and macrotexture toward skid resistance is illustrated in Figure 2.4, taken from Balmer and Hegmon [1980].

Figure 2.4: Interaction of Microtexture and Macrotexture to Provide Skid Resistance
[from Balmer and Helmon 1980 with permission from Transportation Research Board]

As shown, skid resistance measured with the locked wheel friction trailer increases rapidly with increased macrotexture to a mean texture depth of 1.5 mm (with constant microtexture values as measured with the British Pendulum), after which a much smaller rate of increase is observed. Furthermore, in cases where small macrotexture depth is observed, large values of microtexture are required to ensure adequate skid resistance. Upon further inspection of Figure 2.4, it appears that 0.5 mm may be a more appropriate break point between the ranges of rapid and reduced change in skid resistance.

2.3 Pavement Surface Classification

Various pavement surface classification systems have been developed over time. Three such systems are discussed in the following sections.

2.3.1 Nakkel System (Micro and Macrotexture)

A system to classify road surfaces according to geometric form and effects was developed by Nakkel [1973] as shown in Table 2.2. For maximum skid resistance at both low and high speed, pavement surface Types 3 and 5 are desirable. The Type 2 (microtexture only) and Type 4 (microtexture with reduced density of macrotexture) will provide good skid resistance at low to medium speeds, respectively, while Types 1, 6 and 7 are unsuitable.

2.3.2 ASTM Classification (Macrotexture)

ASTM International (formerly the American Society for Testing and Materials) developed procedure ASTM E 559 for classifying pavement macrotexture into four parameters – height, width, angularity and density of the distribution of large particles. Two additional parameters were used to describe the microtexture – harshness and “rugosity” of the background. This standard was withdrawn in 1978 and not replaced.

Table 2.2: Nakkel Classification of Surface Types
(adapted from Nakkel 1973 with permission from the Association of Asphalt Paving Technologists)

Type of Surface	Representation	Description
1		Neither Macrotexture nor Microtexture
2		Only Microtexture
3		Macrotexture and Microtexture
4		Macrotexture and Microtexture (reduced density of Macrotexture)
5		Macrotexture (Due to gaps between coarse aggregates) and Microtexture (due to sharp edged coarse aggregate)
6		Macrotexture (due to gaps between coarse aggregates) but no Microtexture
7		Macrotexture (due to fissures and holes) but no Microtexture

2.3.3 Ontario Pavement Surface Classification Method (“Schonfeld Method”)

A comprehensive texture classification system was developed by Schonfeld [1970] during his employment with the Ontario Ministry of Transportation (MTO). Schonfeld’s method incorporated seven groups of texture parameters having a recognizable effect on the pavement’s skid resistance. A numerical scale of shapes, sizes and/or degrees is assigned to each texture parameter to form a Texture Code Number (TCN) unique to that surface as a whole. Each of the texture parameters A through G are illustrated in Figures 5 through 11.

Schonfeld utilized close range photogrammetry to develop a three dimensional view of the pavement surface and directly measured the texture parameters. Parameters associated with macrotexture (A, B, C and D) were determined with a standard stereoscope (3x magnification), while the microtexture parameters (E, F and G) were determined using a micro-stereoscope (25x magnification).

Height Parameter A is measured in millimeters from the top of the background to the top of the projection.

Scale:

A0	0 mm.
A1	greater than 0 mm. to $\frac{1}{4}$ mm.
A2	greater than $\frac{1}{4}$ mm. to $\frac{1}{2}$ mm.
A3	greater than $\frac{1}{2}$ mm. to 1 mm.
A4	greater than 1 mm. to 2 mm.
A5	greater than 2 mm. to 4 mm.
A6	greater than 4 mm. to 8 mm.
A7	greater than 8 mm. to 16 mm.

Figure 2.5: Texture Parameter A – Macrotexture Height
(from Schonfeld 1970 with permission from Ontario Ministry of Transportation)

Width Parameter B is measured in millimeters and is the horizontal dimension of the projection. It is measured at the level of the top of the background.

Scale:

B0	16 mm. or greater
B1	less than 16 mm. to 8 mm.
B2	less than 8 mm. to 4 mm.
B3	less than 4 mm. to 2 mm.
B4	less than 2 mm. to 1 mm.
B5	less than 1 mm. to $\frac{1}{2}$ mm.

Figure 2.6: Texture Parameter B – Macrotexture Width
(from Schonfeld 1970 with permission from Ontario Ministry of Transportation)

Density of Spacing, Parameter D is estimated as one would estimate the proportion of occupied seats in an auditorium: empty (0), one-quarter full (1), half-full (2), three-quarter full (3), full house (4).

Scale:	D0	No Asperities
	D1	Asperities take up about 25 percent of total area
	D2	Asperities take up about 50 percent of total area
	D3	Asperities take up about 75 percent of total area
	D4	Asperities take up about 100 percent of total area

Figure 2.7: Texture Parameter D – Macrotexture Density
(from Schonfeld 1970 with permission from Ontario Ministry of Transportation)

Angularity Parameter C describes the edges of the projections which may come in contact with the tire.

Figure 2.8: Texture Parameter C – Macrottexture Angularity
(from Schonfeld 1970 with permission from Ontario Ministry of Transportation)

Fine Texture of Projections Parameter E denotes size, sharpness or roundness of the micro-projections on the surface of the stones.

Figure 2.9: Texture Parameter E – Microtexture Size and Sharpness
(from Schonfeld 1970 with permission from Ontario Ministry of Transportation)

Fine Texture of Background Parameter F denotes size, sharpness or roundness of the micro-projections in the background.

denotes size, sharpness or roundness of the

Figure 2.10: Texture Parameter F – Background Micro-projection Size and Sharpness (from Schonfeld 1970 with permission from Ontario Ministry of Transportation)

Undrained Cavities Parameter G indicates the proportion of cavities (depressions or holes) in the background surface, i.e., none, one-quarter, two-quarters or three quarters.

Scale:	G0	No Cavities
	G1	Cavities take up about 1/4 of the total area
	G2	Cavities take up about 1/2 of the total area
	G3	Cavities take up about 3/4 of the total area

Figure 2.11: Texture Parameter G – Undrained Cavity Density
(from Schonfeld 1970 with permission from Ontario Ministry of Transportation)

By analysing thousands of pavement stereographs, Schonfeld was able to relate the texture parameters and TCN to ASTM locked wheel friction trailer test results. The resulting method allows the road authority to then estimate the pavement skid resistance in the absence of a friction trailer, or in areas where testing is not feasible. An example stereo pair is illustrated in Figure 2.12.

Figure 2.12: Example Schonfeld Stereo Pair (Left Photo Top, Right Photo Below)

2.4 Factors Affecting Skid Resistance

2.4.1 Presence and Thickness of Water Film

Exposure to Moisture

The presence of water on a pavement surface is a common occurrence in the North American climate. An FHWA study [1987a, 1987b] was conducted to estimate the amount of time that a pavement is exposed to wet conditions from available weather records. The resulting “wet time” is a combination of rainfall duration, runoff time following rainfall and pavement drying time. Using the model, wet time was calculated for a select number of US states [NTSB 1980]. While desert states such as Arizona experiences only 1-5% wet time, states such as California experiences up to 40% wet time. The average wet time was approximately 15% wet time. Unfortunately, this significant amount of water on the pavement surface dramatically reduces skid resistance and increases the risk of accidents from loss of vehicle control.

Thin Water Films

To examine the effect of water film thickness on pavement surfaces, Csathy [1963] prepared 8 surface specimens including a glass plate, one concrete pavement and 6 asphalt pavements. British Pendulum testing was then conducted with increasing amounts of moisture. The amount of lubricant was controlled by spreading known amounts of water over a known rectangular area before each swing of the pendulum. An atomizer was used to distribute small quantities of water.

Dry BPN values ranged from 118 for an HL-4 asphalt pavement to 86 for the glass plate. Minimum wet readings ranged from 65 to 16 (glass plate) and on average, the reduction in BPN was 50%. Interestingly, 85 to 90% of the reduction in skid resistance was observed by merely wiping the surface with a wet cloth (the thinnest film thickness applied) and 94 to 98% of the

reduction in skid resistance was observed with a nominal film thickness of 0.1 mm. The minimum BPN value was observed between 0.5 to 1.5 mm. With increasing water film thickness, the BPN values actually increased slightly. Csathy [1963] suggests that the additional water offered some resistance itself. It should be mentioned that precipitation may also have a beneficial effect upon skid resistance by washing away contaminants that have collected during dry weather.

Hydroplaning

Extensive research by Horne and Joyner [1965] at NASA has shown that, as forward vehicle speed increases, the tire casing is deflected inward at the forward central portion of the contact area between the tire and pavement surface (referred to as the “footprint”), thus permitting a relatively thick layer of water to penetrate between the tire and pavement surface (Figure 2.13). This thick film region enlarges as the speed increases, gradually extending toward the rear and outside edges of the footprint. Within the thick film region, it is assumed that no asperities in the pavement are in contact with the tire surface and therefore, only hydrostatic forces act upon the tire tread [Daughaday and Balmer 1970]. The area outside of the thick-film region is referred to as the “semidry” area, where each individual load-bearing asperity is either in dry contact with the tire, or the thickness of the water film is small compared to the depth such that the asperity indents the tire material. The hydrodynamic pressures acting in the valleys between load bearing asperities contribute only small support to the total normal load.

Daughaday and Balmer [1970] utilized a model based on Figure 2.13 with a moving axis system such that the water covered pavement approaches the wheel from the positive x-axis with a velocity of $|U|$. The region forward of the footprint is called the inlet region, whereas flow outside of the footprint is referred to as the exterior free surface region because it is composed of surface water and spray with hydrodynamic pressures equal to the atmospheric pressure.

Figure 2.13: Schematic of Tire in Partial Hydroplaning
(reproduced with permission from TRB)

The depth of water on the pavement approaching the inlet region, d is significantly greater than the film thickness between the tire and pavement within the footprint region, h .

Using theoretical and empirical modelling efforts, Daughaday and Balmer [1970] determined lift coefficients for the thick film region, as well as variations of friction coefficient with speed. It is then possible to determine at which forward speed the average hydrodynamic pressure on the thick film region equals the corresponding dry pavement pressure and thus be a potential partial hydroplaning condition.

2.4.2 Speed and Speed Gradient

It is well known that skid resistance on wet surfaces decreases with increasing vehicle speed for most surfaces [Lees and Katekhda 1974]. The rate of decrease, however, varies with

the type of road surface, tire tread pattern, tire width, tire slip and other factors such as tire compound, wheel load and inflation pressure.

At low speed, skid resistance is governed by microtexture (i.e. adhesive forces). As speed increases the contact time between tire and pavement is greatly reduced, thus the adhesion component is reduced. At high speed, the hysteresis component (from the macrotexture) is dominant. On wet pavements, the macrotexture again governs at high speed by providing rapid drainage (referenced elsewhere as *dynamic drainage*) from the tire-pavement interface while the microtexture enables the tire (at any speed) to remove the remaining film of water [Nakkel 1973]. The influence of vehicle speed on the various surface types may be observed in Figure 2.14. As shown, surface Types 2 and 4 display considerable drop in skid resistance at high speed, clearly illustrating the requirement of adequate macrotexture.

Figure 2.14: Behaviour of Different Surfaces in Relation to Speed
(from Nakkel 1973 with permission of AAPT)

The change in skid resistance with speed may be referred to as a *speed-gradient*. Multiple relationships have been developed to model the skid resistance speed gradient. Table 2.3 displays three prominent models to fit skid number (*SN*) and vehicle speed (*V*). The skid number speed gradient (*SNG*) and percentage *SNG* (*PSNG*) are further derived from the models. It has been shown that *PSNG* is a function of macrotexture alone [Henry and Hegmon 1974, Veres et al 1974]. The models are illustrated in Figure 2.15 for three different pavement surfaces.

Table 2.3: Comparison of Skid Number vs. Speed Models
[with discussion from Leu and Henry 1978 and permission from TRB]

Model	Equations	Discussion
2 nd order relation from [Meyer et al 1974]	$SN = a_0 + a_1 V + a_2 V^2$	The parameter a_0 represents low-speed skid resistance and should be related to microtexture only.
	$SNG = -[d(SN)/dV]$ $= -(a_1 + 2a_2 V)$	However, the PSNG equation includes the a_0 parameter, which is in contradiction to previous research stating that PSNG is related to macrotexture only.
	$PSNG = (SNG/SN)*100$ $= [-(a_1 + 2 a_2 V)100/a_0 + a_1 V + a_2 V^2]$	This model may also develop curves that are concave downwards (negative second derivative) or that indicate an increase in SN with speed (refer to Figure 2.16).
Logarithmic relation from Majcherczyk [1974]	$SN = b_0 V^{b_1}$	Majcherczyk found a correlation between b_1 and macrotexture that supports the previous research concerning the relationship between PSNG and macrotexture.
	$SNG = -b_0 b_1 V^{b_1-1}$	However, the model is deficient in terms of its low-speed behaviour. The curve (see Figure 2.15) is too steep and over estimates skid number at low speed. As such, the b_0 parameter cannot be adequately correlated with microtexture.
	$PSNG = (-b_1/V)*100$	
Exponential relation from [Leu and Henry 1978]	$SN = c_0 \exp(c_1 V)$	c_0 represents the zero-speed intercept and is strongly correlated with microtexture. c_1 is proportional to the PSNG and is related to macrotexture. The PSNG equation is speed independent.
	$SNG = -c_0 c_1 \exp(c_1 V)$	
	$PSNG = -100c_1$	The advantages of this model are that it separates the effects of microtexture and macrotexture and provides the expected low-speed behaviour.

Figure 2.15: Skid Number-Speed Models
[from Leu and Henry 1978 with permission from TRB]

In fact, the relationship by Leu and Henry [1978] in Table 2.3 may be rearranged to provide the Pennsylvania State University (PSU) model for skid resistance-speed behaviour. The *SNG* is simply the rate of change of skid number with speed and the *PSNG* is then the percentage *SNG* with respect to that skid number.

As SN_0 is a function of microtexture and *PSNG* is a function of macrotexture, the *SNG* is both a function of micro and macrotexture. Therefore, for two surfaces with the same macrotexture, the one with better microtexture will yield a steeper gradient [Leu and Henry [1978]. Furthermore, Mahone [1976] found that surfaces that originally had a steep gradient would have an intermediate gradient after polishing (i.e. loss of microtexture).

2.4.3 Effect of Traffic and Age

With increased trafficking, the repetitive interaction between the vehicle tires and the pavement surface results in a number of changes to the surface characteristics – usually resulting in a gradual decrease in skid resistance. In flexible pavements, coarse aggregate particles may be dislodged, asphalt cement may migrate to the surface, or contaminants such as tire rubber may be deposited on the surface. More importantly, however, the microtexture of the surface aggregates often polishes under traffic loading, resulting in a significant loss in skid resistance. Under heavy loading conditions, the asphalt mix may be over-compacted within the wheelpaths, resulting in less macrotexture for drainage or the formation of surface ruts that retain rainwater and promote hydroplaning [NCHRP 1972].

The effect of wear and age upon the skid resistance of 24 HL-1 asphalt pavements was investigated by Csathy [1963]. A plot of the British Pendulum Number (BPN) versus Age in years yielded a linear relationship according to Equation 2.1.

$$\text{BPN} = 56.16 - 1.016(\text{Age}) \quad [2.1]$$

The correlation coefficient (r) was -0.60 suggesting low to moderate strength in the linear relationship between BPN and age. The coefficient of determination (R^2) would then be 0.36 indicating that only 36% of the variation in BPN is explained by pavement age – not a very strong relationship. As shown in Equation 2.1, an initial BPN of slightly over 56 was observed during his investigation, with a reduction in skid resistance of approximately 1 BPN per year.

A second analysis of the same data, but plotting BPN versus a “wear factor,” which was defined as the product of pavement age and traffic intensity, divided by a suitable constant in order to work with a manageable number of digits [Csathy 1963]. Traffic intensity was characterized by the average annual daily traffic (AADT) and a constant of 1000 was selected to

reduce the number of digits. A logarithmic relationship was observed between BPN and the wear factor such that the following relationship was determined:

$$\text{BPN} = 65.5 - 7 \cdot \log(0.001 \cdot \text{Age} \cdot \text{AADT}) \quad [2.2]$$

The correlation coefficient improved significantly to between 0.82 and 0.88 depending upon the operator who collected the data (R^2 of 0.67 and 0.77, respectively). Interestingly, the initial value of BPN after construction increased between Equation 2.2 and Equation 2.1 (65.5 versus 56.2, respectively). From professional experience, an initial BPN of 65 for HL-1 is much more realistic and reflects the more accurate model displayed in Equation 2.2.

The results of Csathy [1963] are further supported by research conducted by the Road Research Laboratory [1971], which stated that traffic was the governing factor in the deterioration of the microtexture and structure of the pavement surface. The aging of the pavement surface had little or no effect on microtexture and structure, except that aging generally implied more traffic load applications.

2.4.4 Pavement Type, Materials and Mix Design

Overview

As the pavement friction is governed by microtexture and macrotexture, it follows logically that the two most important factors for constructing skid resistant pavements are the selection of skid resistant and durable aggregates (for microtexture) and using a pavement surface design and construction techniques that optimize surface texture (for macrotexture) [Henry 1996]. For asphalt pavements, surface macrotexture is determined by the aggregate gradation, particle size and shape, whereas macrotexture in concrete pavements is determined primarily by the tining technique used during construction.

Pavement Type

Of the pavement surfaces tested by Csathy [1963], it was found that asphalt pavements offered somewhat better skid resistance than concrete pavements. The type of asphalt cement did not appear to have any effect on skid resistance measurements, whereas the type of aggregate greatly affected the results. Premium aggregates such as traprock provided good skid resistance, whereas Uhthoff limestone aggregates were readily polished under traffic action.

Aggregate Mineralogy

For both asphalt and concrete pavements, the rate of polishing is a factor of the aggregate type or mineralogy of the aggregate used in the surface layer. Dahir and Mullen [1971] investigated the effect of mineralogy toward resistance to polishing. In their investigation, a number of pavement specimens with different aggregate types were subjected to polishing and then tested with the British Pendulum (a surrogate test for microtexture evaluation). Figure 2.16 displays the final BPN values for various aggregate mineralogy. Although friction is also a function of the size and shape of aggregate particles, a number of general observations were made during their research:

- a) the highest permanent skid resistance is obtained by aggregates whose surfaces are continuously renewed by the action of traffic,
- b) Sand sized hard particles embedded in a softer matrix are highly beneficial for improving skid resistance,
- c) Aggregates with uniform mineral composition tend to have higher skid resistance with more angular and larger grain sizes, and
- d) Hardness for uniform aggregates such as quartz pebbles is not always beneficial to skid resistance.

Figure 2.16: Ranking of Various Aggregates After Polishing
[derived from data of Dahir and Mullen 1971]

The concept of utilizing more than one aggregate type with differential rates of polishing has met with some success [Gallaway and Hargett 1969, Gallaway 1967]. As the softer particles wear, the harder particles are left in relief. The shearing action of traffic tires then removes the harder particles. This process is repeated to maintain a particle exposure which contains a preponderance of particles that never remain exposed to the action of traffic long enough to become polished [Gallaway 1973]. The mineral grains must be strongly bonded (by the asphalt matrix) such that non-detrimental, slow differential wear will occur [Henry and Dahir 1979].

Aggregate Size and Gradation

Aggregate gradation has a profound effect on the process of designing the macrotexture into the pavement surface [Henry and Dahir 1979]. On high-speed pavements, it is desirable to provide a high level of surface macrotexture to facilitate rapid water drainage from the tire contact area [AASHTO 1976]. Experience has shown that the coarse aggregates in bituminous mixtures are the predominate aggregates influencing skid resistance whereas it is the fine aggregate that is exposed to the tire in a concrete pavement [Goodwin 1962].

In terms of what size of aggregate particles should be used, there is some consensus that the course aggregate particle size should pass the 19mm sieve and be retained on the 2.36mm sieve. Within this range, it has been shown that halving the nominal maximum aggregate size increases the skid number by about eight units [Hosking 1973, Mullen et al 1974]. This general trend is consistent with Ross [1970], who found that mixes with 3/16-inch material had higher skid resistance than mixes with 3/8-inch material. Csathy [1963] also observed during a comprehensive review of pavement surface friction in Ontario that fine (macro) textures provide superior skid resistance than coarse ones.

Aggregate Specifications

Target aggregate properties to help ensure adequate skid resistance over the life of a pavement surface are shown in Table 2.4.

Table 2.4: Desirable Aggregate Properties for Enhanced Skid Resistance
[derived from data of Dahir 1979]

Property		Value or Range
Moh's Hardness	Hard Fraction	8-9
	Soft Fraction	6-7
Min. Differential Hardness		2-3
Percent of Hard Fraction	Natural Aggregate	50-70
	Artificial Aggregate	20-40
Hard Grains or Crystals	Size (μm)	150-300 (Avg. 200)
	Shape	Angular tips ($\leq 90^\circ$)
Percentage Porosity		25-35
Optimum Pore Size (μm)		125
Aggregate Particles	Size (mm)	3-13
	Shape	Conical, angular ($\leq 90^\circ$)
	Los Angeles Abrasion (%)	≤ 20
	Aggregate Abrasion Value (%)	≤ 8
	Aggregate Impact Value (%)	≤ 20
	Polished Stone Value (PSV)	≥ 75

Aggregate Orientation

Noting correctly that economic considerations generally require the use of local aggregate supplies, Ross [1970] investigated the contribution of aggregate size and orientation toward skid resistance. Using the British Pendulum, Ross determined that skid resistance can be maximized by ensuring random orientation of the aggregate particles, even if the particles themselves are susceptible to polishing. Aggregates susceptible to polishing that were laid flat polished within four to five weeks while randomly oriented (but polish susceptible) particles retained adequate skid resistance even after 1 year of heavy trafficking.

2.4.5 Surface Condition

In addition to polishing of the surface aggregate, other surface distresses may occur to alter the frictional properties of the pavement. Bleeding of the asphalt mix, where excess asphalt cement migrates to the surface giving it a shiny, slick look can cover previously available microtexture and reduce friction.

Excessive roughness caused by distortions in the surface, as well as cracking, can affect vehicle dynamics and cause the vehicle to bounce, thus reducing the effective tire-pavement interface and friction. This effect is particularly pronounced in trucks [Henry 1996].

As already mentioned, the presence of rutting further reduces friction by ponding rainwater and promoting hydroplaning.

2.4.6 Tire Characteristics

The two most important tire characteristics that contribute to skid resistance are the tire tread pattern and the composition of the tire rubber [Goodwin 1973]. The tread pattern must contribute to the removal of water from the tire-pavement interface through the use of circumferential ribs and transverse grooves. Low resilience rubber provides the most hysteresis,

however, readily gains heat and wears more quickly. A balance between low resilience and wear must therefore be struck.

2.4.7 Long Term (Seasonal) Variations

In June 1962, a testing programme was initiated to secure quantitative data on a variety of pavement types in the Province of Ontario concerning the seasonal variation of frictional characteristics [Csathy 1963]. Monthly skid resistance measurements with the British Pendulum Test were collected at six test sites containing 18 test sections. The British Pendulum Numbers ranged from 40 to 70. Based on the results, it was observed that skid resistance is minimal during the months of June, July, August and September and increases significantly in the fall months to a maximum in December and January. A range of 10 BPN was observed as a result of seasonal effects. This range is approximately half of the seasonal variation reported in Britain, which can be as much as 20 BPN [Giles et al 1962, Sabey 1961].

A comprehensive investigation of long term (i.e. seasonal) variation in pavement surface friction was conducted at Pennsylvania Department of Transportation [Dahir et al 1979]. Measurements showed that once a pavement surface had stabilized after being exposed to traffic and weather for one or two years, the surface displayed cyclic skid resistance variation. The surface friction generally decreased to a minimum over the summer months and was rejuvenated to about its original level over the winter season.

As such, the zero-speed skid number (SN_0) must be adjusted to compensate for long (and short) term variations. The value of SN_0 at any time may be found using Equation 2.3.

$$SN_0 = SN_{OR} + SN_{OL} + SN_{OF} \quad [2.3]$$

where SN_{OR} = short term variation adjustment

SN_{OL} = long term variation adjustment

SN_{OF} = measure of SN_0 (independent of short and long term variations)

For asphalt surfaces,

$$SN_{OL} = \Delta SN_0 \exp(-t/\tau) \quad [2.4]$$

where ΔSN_0 = change in SN_0 over testing season (a function of aggregate polish susceptibility)

τ = rate at which polishing takes place (a function of average daily traffic)

t = test day

As shown in Equation 2.4, the long term variation in skid resistance for asphalt surfaces is best characterized by an exponential relationship.

2.4.8 Short Term Variations

Sand and Fine Detritus

Road surfaces are often covered with fine detritus such as sand and other contaminants. In the Canadian environment, salting operations are required to keep road surfaces free of ice and snow, while sand is typically used to provide enhanced traction on snow packed or ice surfaces. However, once the snow pack or ice surface has been removed or has melted, this detritus may itself reduce frictional properties.

As part of his lubrication study, Csathy [1963] also investigated the effect of fine detritus on skid resistance as measured with the British Pendulum. Samples of silt (passing the #200 sieve), fine sand (passing the #100 sieve) and coarse sand (passing the #14 sieve) were used for the investigation. Starting with a clean surface, increasing amounts of detritus were added followed by friction testing. He found that the skid resistance of dry surfaces is reduced as much as 40 to 60% by the presence of fine detritus, whereas the effect of detritus upon wet surfaces was not consistent. The greatest reduction in friction was observed with the coarse sand (57%) followed by fine sand (46%) and silt (39%). It is interesting to note that the reduction in friction observed with coarse sand is greater than the average reduction from water. Although the

specimens covered a wide range of textural characteristics, the detritus effect did not appear to be influenced by the texture of the surface.

The results of Csathy [1963] are consistent with the basic concepts of friction discussed earlier. On dry pavement surfaces, the presence of detritus interrupts the molecular adhesion component of the tire-pavement interaction, thus reducing friction. On wet surfaces, it is likely that two opposing effects are present. The detritus particles decrease the hysteresis portion of the interaction, but provide additional adhesion by reducing the effectiveness of the lubrication. The resultant is small and not well defined.

The effect of road dust (particles with sizes ranging from 5 to 50 μ m) was investigated by Shakeley et al [1980]. A relationship between SN_0 (the zero-speed skid number related to microtexture only) and the amount of dust in grams per square metre of pavement surface ($M1$) was developed as per Equation 2.5.

$$SN_0 = 64.2 - 1862 * M1 \quad [2.5]$$

The equation was developed for a dust loading ranging from 0.0 to 0.007 grams per square metre and a reduction in SN_0 from 62 to approximately 52. The correlation coefficient (r) of 0.82 suggests moderate to good strength in the linear relationship between dust loading and SN_0 . Indeed, 67% of the variation (R^2) in SN_0 is accounted for by dust loading – a considerable influence to say the least.

Interestingly, when the dust loading increased beyond 0.007 g/m², skid resistance (SN_0) increased from 52 to approximately 54. The dust loading of 0.007 g/m² was considered a saturation point after which the effect of dust loading loses its effect [Shakeley et al 1980].

Contamination

In addition to temperature and seasonal effects, pavement surface friction may also exhibit significant short-term variability. Frequent tests during the summer period have indicated

that pavement skid resistance (as tested with the ASTM locked wheel trailer) may vary by as much as 25 percent during a single week [Hill and Henry 1981]. The short term variation in skid resistance has been attributed to build up of contamination on the pavement surface between rainfall events. Two adjustment factors have been developed to model this behaviour. Dahir et al [1979] proposed a Weighted Rain Function (WRF) to account for the time between the testing date and the last rainfall as per Equation 2.6.

$$\text{WRF} = \Sigma(R_i/i) \quad [2.6]$$

where R_i is the rainfall on the i^{th} day prior to the test. Poor correlation was observed between skid number and WRF ($R = 0.20$) and as such, a second measure was developed by Hill and Henry [1981] referred to as the Dry Spell Factor (DSF) in Equation 2.7.

$$\text{DSF} = \ln(t_R+1) \quad [2.7]$$

where t_R is the number of days since the last rainfall of 2.5mm or more (to a maximum limit of 7-days) such that $0 \leq t_R \leq 7$. The resulting correlation coefficient between skid number and DSF was 0.35 – a significant improvement.

With regard to Equation 2.3, the short-term adjustment factor SN_{OR} may be determined using Equations 2.8 or 2.9.

$$SN_{OR} = 1.00 + 2.74 * \text{WRF} \quad [2.8]$$

$$SN_{OR} = 1.14 - 1.17 * \text{DSF} \quad [2.9]$$

Temperature

Field and laboratory studies have shown that pavement friction decreases with increasing temperature. It has been suggested that pavement skid resistance increases inversely with temperature due to the temperature dependence of rubber resilience [Csathy 1963]. The higher the temperature, the smaller the hysteresis losses, and thus the lower the skid resistance values.

However, the exact relationship between pavement temperature, tire temperature and skid resistance values is not fully understood [Meyer and Kummer 1969].

With regard to the Penn State model, the zero-speed skid number is further adjusted for temperature effects according to Equation 2.10 [Hill and Henry 1981].

$$SN_{OR} = 3.79 - 1.17*DSF - 0.104*T_p \quad [2.10]$$

where T_p = pavement temperature (°C). For the Pennsylvania data, a correlation coefficient of 0.35 was observed with this model.

2.4.9 Effect of Gradients and Curved Segments

While stopping distance is greatly affected by the amount of gradient of a road segment due to the effect of gravity, the skid resistance should be fairly constant when compared with level sections. Csathy [1963] compared the British Pendulum Numbers of 16 uphill locations and 14 downhill locations with numerous level sections of the same pavement and found that there was no consistent difference in skid resistance between either the uphill and level sections or the downhill and level sections for either asphalt or concrete pavement surfaces. A slight trend for uphill sections to be less slippery than downhill sections was observed, which was attributed to the higher speeds and more effective polishing action of vehicles travelling downhill.

Csathy [1963] also investigated the skid resistance of straight road sections as compared to horizontal curves, as well as the difference between the skid resistance of the shortest (inside) wheelpaths of curves as compared to the longest (outside) wheelpaths of curves. No difference was observed between the shortest (inside) wheelpaths of curves and straight sections, but the longest (outside) wheelpaths of curves were slightly less slippery than straight sections. Furthermore, the outside wheelpaths were definitely less slippery than the inside wheelpaths. This finding was contrary to what was expected, since the centrifugal effects apply a greater force to the outer wheelpaths than the inside wheelpaths or straight sections for the same vehicle load.

Csathy [1963] suggested that the presence of fine detritus (i.e. sand) may tend to polish the inside wheelpaths (or lanes) more so than the outer wheelpaths (or lanes) due to the slope of the curve and that the outer wheelpaths (or lanes) would tend to be cleaner due to runoff of surface water. However, he cautioned that overall difference in slipperiness associated with gradients, curves and straight and level sections was minor.

The findings of Csathy [1963] are in conflict with others. Balmer [1978] suggests that textural requirements should probably be varied with the geometrics of the highway and with traffic demand.

2.4.10 Road Salts in Lubricant

As already mentioned, the use of road salts is a requirement to provide safe travelling surfaces during the winter months.

During his lubrication study, Csathy [1963] observed that skid resistance was appreciably reduced by the presence of road salts in the lubricant (i.e. water). At a 30% concentration of sodium chloride and water, the average reduction in friction observed was 5 BPN from the straight tapwater value. Calcium chloride has an even greater reduction in friction. At 30% concentration, the calcium chloride solution displayed an average reduction of 7 BPN from the tapwater value. The results are easily explained by the increased lubricant viscosity. With increasing concentrations of road salts, the lubricant viscosity increases. Increased viscosity reduces the drainage capability of the pavement surface, thus reducing friction. It is important to remember that despite lower values of BPN when compared with tapwater, the skid resistance provided by surfaces lubricated with road salt solutions is considerably greater than ice.

2.4.11 Differential Friction

A final topic of interest concerns *differential friction*, a term used to describe the condition that occurs when the individual wheelpaths on which a vehicle rides have different or

unequal coefficients of friction [Burns 1976]. Noting that most friction testing is completed in one wheelpath only, Burns [1976] observed that during stopping distance tests with a skidding car, some pavement conditions caused the vehicle to spin uncontrollably during braking tests. The rotation was caused by unequal friction levels in each of the wheelpaths. Causes for differential friction include bleeding in one wheelpath only, unequal wear, dissimilar shoulder surfacing, unequal drainage and the presence of maintenance patches in one wheelpath only. The results provided strong indication that differential friction may be as important as low friction level in causing wet pavement accidents [Burns 1976].

Hayhoe and Henry [1981] developed guidelines for safe vehicle operation (at an initial skidding speed of 88 km/h) for pavements exhibiting differential friction in the wheelpaths. Figure 2.17 provides recommended maximum tangent lengths under varying levels of differential friction for the safe operation of cars in skidding manoeuvres. The authors are quick to note that Figure 2.17 is for first approximation of the boundaries of safe operation and should only be used as a guide.

Figure 2.17: Maximum Length of Split Friction Coefficient Surface
[from Hayhoe and Henry 1981 with permission of TRB]

2.5 Review of Pavement Friction Measurement Tests and Equipment

2.5.1 Overview

When a tire is braked from a free rolling situation, the friction force experienced by the wheel changes depending upon the slip speed of the test tire relative to the speed of the test vehicle. Slip speed, s is calculated according to Equation 2.11.

$$s = v - v_p = v - \omega * r \quad [2.11]$$

where v is the vehicle speed, v_p is the average tangential speed of the tire, ω is the angular speed of the wheel and r is the average wheel radius. The slip ratio, SR is defined as the ratio of the slip speed to the vehicle speed according to Equation 2.12.

$$SR = \frac{s}{v} * 100\% \quad [2.12]$$

Friction-slip curves for various tire tread depths are illustrated in Figure 2.18. As shown, the maximum friction is normally found at a slip rate between 7 to 20% and can be considerably higher than the locked wheel case (100% slip).

Current friction measurement devices use one of five different principles – locked wheel (100% slip), constant slip (usually between 10 and 20% slip), variable slip (0 to 100% slip), constant slip angle (usually 20 degrees), or the retardation measurement of standard anti-lock braking systems (ABS) [Wallman and Anstrom 2001]. Some of the more popular devices are discussed in the following sections.

Figure 2.18: Friction-Slip Curves
[recreated with select data from Bachmann 1995]

2.5.2 Locked-Wheel Friction Devices

Skid Number (SN) is a standard measurement of pavement friction provided by the ASTM Locked Wheel Friction Trailer [ASTM E-274] and is calculated using Equation 2.13:

$$SN = 100 \cdot F/W \quad [2.13]$$

where F = the tractive force (i.e. the horizontal force applied to the locked test tire at the pavement contact patch) and W = the normal (vertical) load on the test wheel.

The widespread implementation of anti-lock braking systems makes the locked wheel test somewhat outdated, however, the 100% slip condition represents a worst-case scenario and is therefore conservative. A locked wheel friction trailer is shown in Figure 2.19.

Figure 2.19: ASTM Locked Wheel Friction Trailer
(photo courtesy of Ontario Ministry of Transportation)

2.5.3 Constant-Slip Friction Devices

Examples of constant-slip friction devices include the Swedish Skiddometer and the Saab Friction Trailer (Figure 2.20) that apply braking forces to provide constant slip of about 17%. Another widely used device is the GripTester (Figure 2.21) with a fixed slip ratio of 14.5%.

Figure 2.20: Saab Constant Slip Friction Trailer
(photo courtesy of ASFT)

Figure 2.21: GripTester Constant Slip Trailer
(photo courtesy of Findlay Irvine Ltd.)

With reference to Figure 2.18, the constant slip friction devices provide the maximum friction available as opposed to the locked wheel condition (worst case). One operational benefit provided by fixed slip devices is a considerable reduction in test tire wear. In the Netherlands, a friction trailer with 86% slip was developed to better correspond with the locked wheel friction values while reducing tire wear [Wallman and Anstrom 2001].

2.5.4 Variable-Slip Friction Devices

In Norway, Norsemeter AS has developed the ROAR friction trailer (Figure 2.22), which measures the entire friction-slip curve with each measurement cycle (approximately 1 second).

Figure 2.22: Norsemeter ROAR Variable Slip Friction Trailer
(photo courtesy of Ontario Ministry of Transportation)

2.5.5 Constant Slip Angle Devices

A commonly used constant slip angle device is the Sideway-Force Coefficient Routine Measurement (SCRIM) device developed in the United Kingdom by the Transport and Road Research Laboratory [Hosking and Woodford 1976]. The measuring wheel is a special motorcycle wheel mounted with a constant side-slip angle of 20 degrees. The lateral force acting of the freely rotating wheel is divided by the normal load on the wheel to determine the Sideway Force Coefficient (SFC). The SCRIM is illustrated in Figure 2.23. The Mu-Meter (Figure 2.24), which is considerably smaller than the SCRIM, uses a constant slip angle of 7.5 degrees.

Figure 2.23: SCRIM
(photo courtesy of the Québec Ministry of Transportation)

Figure 2.24: Mu Meter
(photo courtesy of Douglas Equipment Ltd.)

2.5.6 Pendulum Devices

The British Pendulum Test (BPT) is a portable, manual device that utilizes the loss in momentum of a swinging pendulum to measure pavement frictional properties. As shown in Figure 2.25, a rubber slider is attached to the end of the pendulum arm, which is raised parallel to the pavement surface prior to each test. Once released, the arm swings down and the slider travels across a pavement surface. The greater the friction of the surface, the greater the loss of momentum of the arm and the less amount of “back-swing.” A pointer follows the arm after the slider has left the pavement surface and measures the resulting British Pendulum Number (BPN).

The BPT is widely used due to its simplicity, low cost and large historical database. Perhaps the most beneficial aspect of the BPT is that it is considered a surrogate for estimating microtexture – although no direct methods are currently available for measuring microtexture [Titus-Glover and Tayabji 1999].

Figure 2.25: British Pendulum Test

2.5.7 Texture Measurement Tests and Devices

As already mentioned, the pavement surface roughness is characterized by two sets of parameters – elevations (normal to the surface) and textures (in plane with the pavement surface). Furthermore, the elevation and texture features are related to each other. Thus, all texture measurement devices have two sets of limitations; the largest and smallest differences of height that the device can resolve, as well as the longest and shortest wavelengths that it may measure [Thomas 1982].

Stylus Methods

Using the same principles as the phonograph (aka “record player”), stylus instruments measure roughness by passing a sharp probe across the surface under investigation. The movement of the probe is generally amplified and converted into electrical oscillations using a transducer. The vertical range of a stylus instrument is governed by the dynamic range of the transducer as well as background vibrations and thermal noise associated with electronic devices. Furthermore, the stylus is not a “mathematical point,” but a probe with finite dimensions [Thomas 1982]. As such, the resolution is further constrained by the size of the probe itself. Finally, the one-dimensional nature of the stylus does not allow for time/resource efficient surface (i.e. area) mapping.

Sand Patch Test

The sand patch method uses a known volume of fine sand, which is poured on the pavement surface and spread evenly to cover a circular patch levelled with the tips of the asperities. The diameter of the patch is measured and the mean texture depth (MTD) is obtained by dividing the volume of sand by the circular area covered [Lees and Katekhda 1974]. The sand patch test is shown in Figure 2.26.

Figure 2.26: Sand Patch Test
(from Lees and Katekhda 1974 with permission from TRB)

The method has poor repeatability and there is no justification in relating the average texture depth to the drop in friction with speed since unconnected voids in the surface are included in the measurement while they play an idle part in dissipating the water between the tire and the road surface [Lees and Katekhda 1974]. The degree of packing of the sand may also contribute to errors in the results. Finally, the size of the sand particles prevents the measurement of very fine channels. The test is easy and inexpensive to complete, however and therefore is widely used.

Grease Patch Test

The Grease Test was developed by the National Aeronautics and Space Administration (NASA) in the late 1960's [Leland et al 1968]. Very similar in concept to the Sand Patch Test, the Grease Test involves working a known volume of grease into the pavement surface and measuring the resulting grease-cover area. The average pavement texture depth is then calculated by dividing the known volume of grease by the resulting grease-cover area. The Grease Test is

very simple to complete and the grease is able to penetrate macrotexture too fine for the sand used in the Sand Patch Method. However, the method leaves a greasy area on the pavement surface and, as with the sand patch test, idle voids are included in the measurement [Lees and Katekhda 1974].

Surface Print Methods

Surface print methods measure the number of asperities within a unit area. Testing may be conducted with aluminum foil, inks and dyes, or other emulsions. An experienced operator is required to evaluate the resulting prints and the number of asperities is dependent upon the pressure applied to the surface during the test [Lees and Katekhda 1974]. No indication of particle size, shape and depth is available from surface print methods.

Flow Methods

The mean hydraulic radius of the spaces between asperities of a pavement surface may be determined using the Outflow meter developed by Moore [1966]. As shown in Figure 2.27, a weighted cylinder open at each end stands upright on the pavement surface. The time required for the water level in the cylinder to drop a given height is used to calculate the mean hydraulic radius between the pavement macrotexture and the end of the cylinder in contact with the surface (covered by a rubber ring). The finer the texture, the smaller the hydraulic radii. The instrument was developed in a study of hydroplaning of pneumatic tires on wet roads. A theoretical relation between the mean hydraulic radius and the slope of friction/speed lines was developed.

A high pressure version of the outflow meter was also developed, but no correlation with road friction behaviour was reported [Lees and Katekhda 1974]. Advancement of the outflow meter apparatus was conducted at Birmingham University [Lees and Katekhda 1974], where through extensive field investigation, developed relationships between locked wheel friction trailer test results and macrotexture as measured by the outflow meter.

Figure 2.27: Outflow Meter
(from Lees and Katekhda 1974 with permission from TRB)

Moulding Methods

Moulding methods include negative and positive moulds. For negative moulds, a mastic compound is pressed into the pavement surface, removed and allowed to harden. Measurements of size, shape and number of particles and channels may then be taken. For positive moulds, plaster of Paris is injected into the pavement surface and allowed to harden. Successive sections of the surface are imaged and removed to develop a three dimensional representation of the

surface. While accurate measurements may be obtained with moulding methods, they are time consuming, applicable to localized testing only and are therefore not routinely conducted.

Text-Ur-Meter

The Text-Ur-Meter is a small, hand operated instrument for evaluating pavement surface texture. The device consists of 29 parallel rods that are evenly spaced in a single line across its 254 mm (10-inch) length. The rods may move independently of one another in the vertical direction, however, each is connected to a single taut cord that passes through the entire series of rods. This cord is connected to a dial gauge that reads zero when all rods are in line vertically. When placed on a pavement surface, the rods move up and down to form to the shape of the surface, which causes tension in the cord and a corresponding reading on the dial gauge. The coarser the texture, the more movement in the rods and thus the higher the reading on the dial gauge (0.001 inch increments). The Text-Ur-Meter is a very simple device to use and can take many measurements in rapid succession.

Optical Methods

A number of optical methods have been developed for texture measurement. Strutzemberger and Havens [1958] developed the “reflectometer” - a system of measuring the change in the texture of stone due to polishing using a collimated beam of light projected onto the surface of a sample at 30 degrees. The light reflected at 30 degrees to an optical sensor was recorded and compared with the amount of light projected. Losses in the reflected light at 30 degrees were considered a result of the texture.

More recently, high-speed laser systems have been developed to measure pavement texture. Using sampling frequencies of up to 80,000 Hz, these systems are capable of measuring macrotexture, but not microtexture.

2.5.8 Sources of Variability

As with any measurement system, it is important to understand potential sources of variability or error when collecting pavement friction measurements. As will be discussed in the following paragraphs, sources of error with friction measurement devices are considerable and must be accounted for to obtain reliable results.

During his considerable research concerning skid resistance of pavement surfaces in Ontario, Csathy [1963] also investigated factors that affect the results of the British Pendulum test itself. For example, consistent differences in the order of 1 to 6 British Pendulum Numbers were observed between measurements taken by different operators on the same surface. The angle of inclination of the test surface also appeared to influence the measurements obtained with the pendulum test, suggesting that it is not well suited for measurement of skid resistance on gradients or curved sections of roadway without adjustment to the recorded values.

Achieving consistency between individual trailers (and even replicate tests of the same pavement) has been problematic for locked wheel trailers. Indeed, continuous, time consuming and expensive calibration appears to be required to minimize (but not eliminate) such inconsistencies. The problem of calibration and establishing correlation between skid trailers was so great that the Ohio State University constructed the Field Test and Evaluation Center for Eastern States (EFTC) to provide calibration of water delivery systems, force measurement systems and speed calibration systems [Whitehurst and Gallogly 1976].

Variation in tire rubber composition and geometry may affect friction measurements. As reported by the Dutch Road Research Laboratories [KOAC-WMD 2000], differences between friction values obtained with PIARC test tires manufactured in 1975, 1984 and 1998 were observed due partly to rubber compound chemistry. The differences were found to be so great between the tires manufactured in 1975 to those in 1984 and 1998 that a correction formula was

developed by the Netherlands to account for the variation. Meyer et al. [1974] list a number of factors responsible for errors in locked-wheel pavement skid resistance tests and the average error band associated with each type of error (Table 2.5).

Table 2.5: Error Sources for Locked Wheel Friction Tests

Factor	Average Error Band (SN)
Speed Holding	± 1.5
Pavement Variability	
Lateral	± 4
Longitudinal	± 2
Dynamic Wheel-Load Change	± 1
Data Evaluation by Operator	± 3

Although the magnitude of these errors may be reduced through (extensive) calibration and other precautions, it is clear that significant variation between both individual trailers and between replicate tests with the same trailer may easily occur.

More recently, the Washington State Department of Transportation provided a comprehensive study of the various random and systematic errors (and their respective magnitudes) on friction test measurements [Corsello 1993]. Table 2.6 provides the results of that study, which are in general agreement with those of Meyer et al. [1974].

From Tables 2.5 and 2.6, it is clear that considerable effort must be expended to calibrate existing measurement devices to help ensure accurate and repeatable data.

Table 2.6: Sources of Random and Systematic Error for Locked Wheel Friction Tester

Error Source	Random	Systematic	Effect on Skid Resistance
Speed Holding	X		At 65 km/h, ± 2 SN per km/h
Speed Measurement		X	At 65 km/h, ± 2 SN per km/h
Water Temperature		X	Negligible
Air Temperature		X	Indirect effect through pavement and tire temperature
Pavement or Tire Temperature	X		± 4 SN per 5.5°C
Water Film Thickness	X	X	± 1 SN for $\pm 10\%$ variation
Water Flow		X	Strong
Pavement Variability (transverse)	X		± 10 SN
Pavement Variability (longitudinal)	X		± 10 SN per km
Tire Variability		X	2.5 SN
Tire Condition		X	1 SN within wear range
Inflation Pressure		X	1 SN within operating range
Wheel Load Error		X	% SN error equal to % weight error
Wheel Load Range		X	1 SN per 45 kg
Instrumentation	X	X	Drift
Operating Procedure	X	X	Controls other error sources

2.6 Skid Resistance Correlation Studies

2.6.1 Early Correlation Studies

First International Skid Resistance Conference

As early as the late 1950's, it was apparent that there was no accurate method of comparing results obtained from various skid resistance testing devices [Smith and Fuller 1969]. This included both results from the same type of measurement device (i.e. between individual skid trailers), as well as between different types (i.e. skid trailer vs. portable test). To address

these discrepancies, the First International Skid Prevention Conference was held in Charlottesville, Virginia in 1958. Two weeks prior to this conference, a field correlation study was held to collect and compare data from various devices. Probably the most significant findings from the field tests were the lack of agreement among and between the skid trailers and the influence of the water film thickness on skid number [Goodwin 1973]. Overall, the differences between devices were found to be both quantitative and qualitative and indicated a need for further “correlation studies” [Moyer 1959]. As a result of this conference, interest in the topic was so great that the ASTM Committee E-17 on Skid Resistance was formed thereafter.

Tappahannock Skid Conference

Another such study was completed in the summer of 1962 by the (then) Virginia Council of Highway Investigation and Research and included 21 agencies [Dillard and Mahone 1963]. Devices compared included skid trailers, stopping-distance vehicles and portable testers. For the skid trailers, the extent to which the trailers agreed was dependent upon speed as well as site friction level. Furthermore, no satisfactory correlation was obtained between the skid trailer test results, the stopping distance automobiles or the British Pendulum testers [Goodwin 1973].

The ASTM E-17 Committee reviewed the resulting data and concluded that despite numerous improvements in the skid trailers, the spread in data was statistically significant [Smith and Fuller 1969]. Thus, the results from individual trailers were not sufficiently accurate for comparison purposes. The ASTM Committee promptly developed improvements to the device specifications.

Florida Skid Correlation Study

A third correlation study was required to determine the effectiveness of the specification improvements. Therefore, in 1967 the Florida State Road Department partnered with the (federal) Bureau of Public Roads to organize and carry out another round of comparisons.

Unfortunately, the primary conclusion from this study was that while some agreement was achieved among trailers, standardization of the skid trailer as an acceptable uniform testing method had not been achieved at that time [Smith and Fuller 1969].

2.6.2 World Road Association (PIARC) Harmonization Project

As the principle of measurement differs between friction measurement equipment, it is possible that a diverse range of friction data could be obtained on the same highway under the same conditions using different devices [Al-Qadi et al 2002].

To overcome this problem, the World Road Association – formerly known as the Permanent International Association of Road Congresses (PIARC) – conducted a comprehensive full-scale experiment in 1992 to harmonize friction measurements from several internationally used friction devices [PIARC 1995]. The following excerpt is from the minutes of the PIARC Committee On Surface Characteristics (C1) from their 1995 meeting in Montreal, Canada concerning the international experiment:

In total 16 countries participated and performed 51 different measurements of friction or texture on 54 sites evenly distributed in Spain and Belgium among which 10 were on airfields. As the measurements were made at different speeds and repeated at least twice, the database includes about 16,000 measurement data as well as the relevant information on the sites, the equipment and the measurement conditions. The friction devices were of various types: locked wheel, retarded wheel, ABS, variable slip, side force, pendulum and some new prototypes. The texture was measured by means of the sand patch, laser profilometers using the triangulation method, an optical system using the light sectioning method and outflow meters.

The primary outcome of the data analysis exercise was the development of the PIARC Model – a modified version of the Penn State Model (discussed in Section 2.4) that allows the

friction value to be made at any speed – not simply one of the test speeds used during the experiment [PIARC 1995]. Based on the PIARC Model, the International Friction Index (IFI) was developed to allow comparison between different friction devices and estimate friction values at all speeds. The IFI is composed of two values – a “Golden” speed constant (Sp) and a “Golden” friction value at 60 km/h ($F60$). The IFI is then reported as $IFI(F60, Sp)$ – not a single value such as provided by the International Roughness Index (IRI).

The speed number (Sp) is determined from a texture measurement and regression constants determined during the data analysis phase of the PIARC experiment according to Equation 2.14.

$$Sp = a + b * Tx \quad [2.14]$$

where Tx is the texture measurement and a and b are regression constants for the texture measurement device. Once Sp is calculated, the $F60$ parameter is calculated using Equation 2.15.

$$F(60) = A + B * FRS * e^{\frac{S-60}{Sp}} + C * T \quad [2.15]$$

where A and B are regression constants for the specific friction device, C is a regression constant to adjust the texture measurement T if a ribbed tire is used on the friction test device ($C=0$ if a smooth tire is used). FRS is the friction measurement measured at slip speed S . With these two parameters calculated, the Golden friction value at any slip speed, $F(S)$ can be estimated using Equation 2.16.

$$F(S) = F(60) * e^{\frac{60-S}{Sp}} \quad [2.16]$$

Using the regression constants developed during the experiment, the friction values expected from other measurement devices may also be determined for the pavement under investigation.

2.7 Previous Efforts to Estimate Macrotexture from Mix Properties

A review of the literature indicated that other similar efforts have been conducted. During an investigation into the measurement of hot mix asphalt segregation, Stroup-Gardiner and Brown [2000] developed a relationship between the estimated texture depth (*ETD*, mm) and various gradation properties including the maximum aggregate size of the mixture (*MAS*, mm), the percentage passing the 4.75mm sieve (*P4.75*, %), the coefficient of curvature of the gradation curve (*Cc*) and the coefficient of uniformity of the gradation curve (*Cu*) as shown in Equation 2.17 with the corrected sign for the coefficient of uniformity reported by McGhee et al [2003].

$$ETD = 0.01980(MAS) - 0.004984(P4.75) + 0.1038(Cc) + 0.004861(Cu) \quad [2.17]$$

The *ETD* parameter was not an actual MTD value from a sand patch test, but was an estimated value calculated from a linear transformation of MPD. The model was reported to have an R^2 value of only 0.65 [Stroup-Gardiner and Brown 2000].

In addition to somewhat poor predictive capacity, the use of both the coefficient of curvature and the coefficient of uniformity within the same model (without some type of transformation) is not a sound statistical practice since they are correlated to one another (i.e. not independent variables).

Another model was developed by Flintsch et al. [2003] from data collected at the Virginia Smart Road using a laser sensor developed by International Cybernetics Corporation (ICC). The estimated texture depth using the ICC system (*ICCTEX*, mm) was related to the nominal maximum aggregate size of the mix (*NMAS*, mm) and the voids in the mineral aggregate (*VMA*, %) according to Equation 2.18 with an R^2 of 0.97 [Flintsch et al 2003].

$$ICCTEX = -2.896 + 0.2993(NMAS) + 0.0698(VMA) \quad [2.18]$$

Although McGhee et al [2003] reported that neither Equation 2.17 or 2.18 worked well for large stone or coarse-graded mixes, it is not certain whether or not a polynomial relationship was attempted.

A subsequent review of Equations 2.17 and 2.18 was conducted by Prowell and Hanson [2005] during an analysis of the National Centre for Asphalt Technology Test Track using the Circular Texture Meter (CTM). The CTM is a laser-based device for measuring MPD at a static location as an alternative to the sand patch method. A stepwise regression analysis of 2003 Test Track mix data determined that a second order polynomial relationship between fineness modulus and MPD from the CTM (in mm) provided the best macrotexture estimation [Prowell and Hanson 2005] as shown by Equation 2.19 ($R^2=0.93$). Fineness modulus is calculated by summing the percentages retained on the 0.150, 0.300, 0.600, 1.18, 2.36, 4.75, 9.5, 19.0, 37.5, 75 and 150mm sieves and dividing by 100 as outlined in ASTM C136.

$$MPD_{(CTM)} = 0.2421(FM)^2 - 1.576(FM) + 2.727 \quad [2.19]$$

While Equation 2.19 appears to provide excellent predictive capability for estimating MPD, it suggests that only the aggregate gradation controls the constructed mix texture. In other words, modifying other mix properties such as asphalt cement content and compactive effort would have no significant influence upon the resulting texture, which does not seem reasonable. It is possible that the mixes investigated by Prowell and Hanson [2005] had a small range of asphalt cement content such that the regression analysis did not display significant contribution toward macrotexture.

CHAPTER 3 - DIGITAL IMAGE ANALYSIS OF ROUGH SURFACES

3.1 Chapter Objective

Whereas Chapter 2 focussed upon previous research and existing techniques specifically related to pavement friction and texture, the objective of Chapter 3 is to introduce various digital image analysis techniques that have been used to quantify surface topography - not necessarily pavement surfaces – and discuss how they might be used for the current investigation.

3.2 Background

The determination of the topography of friction surfaces is a basic requirement for the analysis, interpretation and understanding of mechanical friction processes [Hemmleb and Albertz 2000]. Although the application of close range photogrammetry and morphometric image analysis of pavement surfaces is not unique, it is under-developed. Investigations in England [Sabey and Lupton 1967] by the Road Research Laboratory (RRL), now the Transportation Research Laboratory (TRL) and in Canada [Schonfeld 1968, 1970] by the Ontario Department of Highways (DHO), now the Ministry of Transportation (MTO) began in the late 1960's to observe and quantify pavement micro and macrotexture objectively using close range photogrammetry.

While extremely promising results were observed, the methods did not flourish into mainstream practice for one major reason - the analysis methods available at the time (i.e. viewing the hardcopy stereographs and manually measuring heights) were extremely slow and costly. Schonfeld [1970] reported that the analysis of a single pair of stereographs required at least one hour and that five to ten stereo-pairs were needed to represent a single pavement section. Therefore, the method was simply not feasible outside of the research world. Schonfeld

was in the unfortunate situation where his comprehensive analysis method was severely limited by the technology of the time.

Fortunately this is no longer the case. Modern technology and analysis techniques will allow replication and advancement of the original research in a fraction of the previously required processing time. Many different image analysis techniques are available to investigate these issues, although they may be broadly grouped into four categories as follows:

- a) Amplitude Parameters,
- b) Texture Parameters,
- c) Fractal Analysis and Lacunarity, and
- d) Surfaces in Three Dimensions (3D)

In the following sections, various analysis techniques are described for the above categories, as well as how the results of previous research efforts might aid the current investigation.

3.3 Amplitude Parameters

Amplitude parameters represent the first historical measures for roughness characterization as they are used to evaluate the elevation profile of a surface – first provided by stylus instruments.

3.3.1 Extreme Value Parameters

Early profiling instruments such as the light section microscope were only able to provide extreme value parameters of a surface under investigation – usually the vertical separation of the highest peak and lowest valley of the profile, referred to as Pt [Thomas 1999]. The advent of electrical filters allowed the measurement of other parameters such as the height of the highest peak above the mean line, Rp and the depth of the lowest valley below the mean line, Rm . A

more useful peak-to-valley definition is called the ten-point height, R_z – defined as the vertical separation of the average of the five highest peaks and the average of the five lowest valleys.

Extreme value parameters, however, are unrepresentative of the surface as their values may vary widely for different sampling lengths and do not provide information concerning the distribution of peaks and valleys across the surface. Furthermore, extreme value parameters are also dependent upon the definition of a peak or a valley, not always obvious for some surfaces.

3.3.2 Average Value Parameters

As stylus instruments became more sophisticated, average value parameters of a profile could be determined. In the United States, electrical signals from the stylus were passed through an AC voltmeter, which responded to the root mean square (RMS) average voltage of the signal, thus the RMS roughness, R_q of a profile was defined as [Thomas 1999]:

$$R_q = \sqrt{\frac{1}{L} \int_0^L z^2(x) dx} \quad [3.1]$$

where L is the evaluation length of the profile and z is the depth or elevation at any point.

In Europe, the AC signal from the stylus was passed through a rectifier to charge a capacitor and thus defined the centre-line average (CLA) roughness, R_a as:

$$R_a = \frac{1}{L} \int_0^L |z(x)| dx \quad [3.2]$$

The CLA height is defined as a line conforming to a prescribed geometrical form of the profile throughout the sampling length such that the sums of the areas contained between it and those parts of the profile which lie on either side of it are equal [Orchard et al 1970].

Other measures include the peak to valley average height, profile length per unit of centreline length (P/L), mean hydraulic radius (MHR), and profile length per asperity. Table 3.1 displays different surface profiles with their respective measurement [Orchard et al 1970].

Table 3.1: Comparison of Measures of Surface Texture
[Orchard et al 1970 with permission of AARB Group Ltd.]

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
CLA Ht.	1.6	2	2	4	2	4	2	1.3
Avg. Depth	2	4	4	4	2	4	2	2
RMS	1.4	2.5	2.5	4	2	4	2	1.4
<i>P/L</i>	1.6	4.1	2.2	3	3	5	2	2
A_2 /Avg. Depth	6.3	4	8	8	4	4	8	6
P/A_1	0.12	0.51	0.14	0.09	0.37	0.31	0.13	0.25
Mean Hyd. Rad.	1	0.8	1.2	1.3	0.7	0.8	1	0.9
MHR/L	0.08	0.2	0.15	0.17	0.17	0.2	0.13	0.14
Asp. Ht./Pitch	0.5	2	1	1	1	2	0.5	0.5
P/No. of Asp	1.23	1.64	1.76	2.4	1.2	2	1.6	1.2

L = Length, P = Profile length, A_1 = Area between L and P, A_2 = Area between crest line and profile,

Table 3.1 is useful for observing whether a specific measure can differentiate between profile types. With reference to the Nakkell and Schonfeld classification systems presented earlier, it may be expected that Profiles 2 and 3 would yield the highest skid resistance, followed by Profiles 4, 5 and 6, then Profiles 7 and 8, with Profile 1 having the least skid resistance.

However, while Profiles 2, 3, 5 and 7 vary considerably in terms of coarseness and sharpness, they yield the same value of CLA. Similar values of average depth are also observed for all profiles. The P/L measure provides more variety in results and generally ranks the profiles according to the expected skid resistance. Interestingly, the P/L measure is actually one method used to determine the fractal dimension of a transect, which will be discussed in Section 3.4.

Other measures that appear suitable for skid resistance characterization include the profile length divided by the area between the centreline and profile (P/A), as well as the profile length

per asperity [Orchard et al 1970]. While the mean hydraulic radius does not necessarily rank the profiles in the correct order of anticipated skid resistance, it does provide an accurate indication of drainage potential. For example, Profile 1 yields greater MHR than Profile 5, which appears reasonable in terms of the volume of water that could be expelled by each profile.

3.3.3 Height Distribution

While average value parameters provide more information than extreme values, they do not measure the spatial variation of the profile – i.e. the variation in height from point to point of the surface [Thomas 1999]. The variation in surface heights may be represented by a statistical distribution – specifically the probability density $p(z)$ of a distribution of heights as shown in Figure 3.1. The probability of a height lying in between z and $z+dz$ is $p(z)dz$, and the cumulative probability that a height will be below some level h is according to Equation 3.3.

$$P(h) = \int_{-\infty}^h p(z) dz \quad [3.3]$$

Figure 3.1: Profile Height Distribution $p(z)$ and Cumulative Height Distribution $P(z)$
[from Thomas 1999]

The probability distribution $p(z)$ has a mean height line through the profile that can be characterized by its central moments according to Equation 3.4:

$$\mu_n = \int_{-\infty}^{+\infty} z^n p(z) dz \quad [3.4]$$

The second moment (n=2) is referred to as the variance, which describes the excursions of the distribution from its mean roughness [Thomas 1999]. The square root of the variance is the standard deviation and is numerically equal to the RMS roughness, Rq .

The third central moment (n=3) is the skewness, Sk , and is a measure of the asymmetry of the distribution. Most machined surfaces are slightly negatively skewed as the peaks are more easily removed than valleys [Thomas 1999].

The fourth central moment (n=4) is called kurtosis and describes the overall shape or “peakedness” of the distribution.

3.3.4 Bearing Area

With regard to a profile distribution, the bearing area at a given height may be defined as the proportional length of all the plateaux resulting if the surface were abraded down to a level place at that height. Mathematically, the bearing area at height, h is simply the compliment of the cumulative probability distribution function according to Equation 3.5 [Thomas 1999].

$$tp = \int_h^{+\infty} p(z) dz = 1 - P(h) \quad [3.5]$$

For a Gaussian height distribution, the function $P(h)$ is tabulated in terms of Rq , so if Rq is known, the numerical value of tp at any height may be found by inspection as illustrated in Figure 3.2.

Figure 3.2: Derivation of the Bearing Area of a Gaussian Height Distribution
[from Thomas 1999]

3.4 Texture Parameters

3.4.1 Introduction

Description of a surface restricted to its variations in amplitude will be incomplete for practical purposes [Thomas 1999]. It is therefore necessary to find some convenient means of describing the variation in height within the plane of the surface.

When analyzing digital imagery, a *discrete tonal feature* is a connected set of pixels that all have the same (or very similar) brightness value [Jensen 1996]. When a small area of an image (e.g. a 3 by 3 pixel area) displays little variation of discrete tonal features, the dominant property of that area is a *grey shade*. If, however, a small area displays wide variation of discrete tonal features, the dominant property of that area is *texture*.

Texture classification may be completed using several approaches including first and second order grey level (i.e. pixel brightness) statistics in the spatial domain, as well as in the frequency domain using the Fourier transform. Table 3.2 displays a summary of the various texture classification techniques that will be discussed in more detail in the following sections.

Table 3.2: Texture Classifiers in 2-D Image Analysis

Spatial Domain				Frequency Domain
Statistical			Structural	Fourier Transform
Window		Lag, Semivariance	Triangulated Primitive Neighbourhood	
First Order	Second Order	Autocorrelation, Cross Correlation, Spectral Analysis		

3.4.2 First-Order Grey-Level Statistics in the Spatial Domain

When analyzing large quantities of data, it is extremely useful to determine summary statistics such as averages, standard deviations, etc. to establish an overall characterization of the sample population under investigation. Similarly with image analysis, the brightness value statistics in local areas (i.e., kernels) may provide much information toward texture classification.

A number of first order statistics (i.e. statistics calculated on groups of individual pixel brightness values) are available for texture classification. Hsu [1978] used 17 first order texture measures to classify land cover imagery from aerial photography and noted that all measures except kurtosis were statistically significant. The most commonly used measures include mean, standard deviation, variance, kurtosis and entropy. First order statistics are simple to calculate, but do not account for the spatial relationship between pixels in terms of the probability of occurrence of grey level pairs in pixels of close proximity.

3.4.3 Second-Order Grey-Level Statistics in the Spatial Domain

To account for the spatial dependency of brightness values, a higher order of texture measures was proposed by Haralick [1979, 1986] based upon grey level co-occurrence matrices (GLCM). Jensen [1996] describes the concept of higher order statistics as follows:

If $c = (\Delta x, \Delta y)$ is considered a vector in the (x, y) image plane, for any such vector and for any image $f(x, y)$ it is possible to compute the joint probability density of the pairs of brightness values that occur at pairs of points separated by c . If the brightness values in the image can take upon themselves any value from 0 to the highest quantization level (quant_k) in the image (typically 255), this joint density takes the form of an array (matrix), h_c , where $h_c(i, j)$ is the probability that the pairs of brightness values (i, j) occur at separation c . This array h_c is quant_k by quant_k in size.

In other words, one may examine the spatial dependence of brightness values by examining the probabilities that pairs of brightness values occur within designated areas (e.g. kernels). The GLCM is formed by counting the number of times each pair of brightness values occurs at varying separations and directions ($c = (\Delta x, \Delta y)$) within each kernel. It is assumed that all textural information is contained in the brightness value spatial-dependency matrices that are developed for angles (directions) of 0° , 45° , 90° and 135° [Jensen 1996].

In general, the greater the number found in the diagonal of the co-occurrence matrix, the more homogeneous the texture for the kernel. In order to extract more quantitative textural information from the co-occurrence matrices, a number of additional measurements may be applied. Widely used measures are Angular Second Moment (measure of homogeneity), Contrast (range of grey levels), Entropy (randomness of grey levels), Inverse Difference Moment (lack of variability) and Correlation.

3.4.4 Semivariance and the Semivariogram

To measure the spatial dependence of continuously varying phenomena (i.e. areas that are continuous, random or have unlimited variability), the theory of regionalized variables may be applied. The key to this analysis is the *semivariogram*.

Consider a transect (straight line) of pixels, x with brightness value (or elevation value), z at regular intervals along the transect, $z(x)$ as shown in Figure 3.3. The relationship between a pair of pixels at h intervals apart, also referred to as the *lag* distance, is given by the average variance of differences between all pairs. The per-pixel variance is mathematically one-half of the average variance, so that the *semivariance* for pixels x and $x+h$ may be calculated as one-half of the difference in brightness value (or elevation) between the 2 pixels raised to the second power. The average semivariance for the transect is denoted $Y(h)$ according to Equation 3.6.

$$Y(h) = \frac{1}{2m} \sum_{i=1}^m [z(x) - z(x+h)]^2 \quad [3.6]$$

The greater the value of $Y(h)$, the more dissimilar the pixels. The semivariogram is formed when $Y(h)$ is plotted against lag distance, h as shown in Figure 3.4. The semivariance at distance $h = 0$ is zero, as there are no differences between points compared to themselves. As pixels are compared to each other at increasing h , the semivariance increases until it becomes approximately equal to the variance of the surface itself after which there is no change in semivariance with increasing lag (i.e., there is no spatial dependence between pixels at lags greater than the range).

Figure 3.3: Transect of Pixels

Figure 3.4: Typical Semivariograms

As indicated in Figure 3.4, the value of h where this occurs is called the range, while the actual value of semivariance at the range is called the sill. The nugget represents unresolved, sub-grid scale variation or measurement errors and is represented as the intercept of the semivariogram with the y-axis. The Spatially Dependent Structural Variance (SDSV) is the difference in semivariance between the nugget and the sill and indicates the portion of the semivariance that may be attributed to the spatial dependence of the pixel pairs.

An important concept within semivariance analysis concerns the “support” as defined by Olea [1990] as:

“An n -dimensional volume within which linear average values of a regionalized variable may be computed. The complete specification of the support includes the geometrical shape, size, and orientation of the volume. The support can be as small as a point or as large as the entire field. A change in any characteristic of the support defines a new regionalized variable. Changes in the regionalized variable resulting from alterations in the support can sometimes be related analytically.”

Comprehensive discussion concerning how the support affects the resulting semivariance analysis may be found in Dungan [2001].

Furthermore, the shape of the semivariogram (Classical, Periodical, Aspatial or some combination) is indicative of the spatial pattern, as well as the transect orientation. A classical or spherical shape is usually observed from randomly oriented transects on grassland. A periodic semivariogram indicates repetitive pattern such as a transect oriented across a checkerboard (often found in farmland). An aspatial shape may be observed when analyzing homogeneous soil or along plough lines.

Semivariograms may be calculated at all scales of spatial variation. In addition to image characterization, the semivariogram is useful for the selection of required image resolution for analysis purposes. Selection of the lowest possible resolution, while retaining acceptable spatial variability, reduces processing time. Furthermore, the semivariance analysis can assist in the selection of kernel size for co-occurrence matrix analysis. Specifically, the range of the semivariogram indicates the point where spatial independence is achieved. Therefore, kernels smaller than the range do not capture image variation sufficiently, while kernels larger than the range contain redundant information.

Finally, the semivariogram is extremely useful for characterizing surface roughness using fractal analysis, which will be discussed in Section 3.5.

3.4.5 Structural Texture Analysis

The *triangulated primitive neighbourhood* (TPN) method is derived from psychophysical theory of human texture perception. The method involves the development of *texture primitives*, which are larger than individual pixels and observing the spatial arrangement of the primitives.

3.4.6 Frequency Domain Operations

The previously mentioned techniques are performed in the spatial domain. Images may also be filtered and analyzed in the frequency domain, through the use of the Fourier Transform and others. The underlying premise of the Fourier Transform is that any continuous function, $f(x)$ may be represented by a summation of series of sine and cosine terms, $F(u)$ of varying spatial frequencies. The Fourier Transform is extended to 2-D, $F(u,v)$ for image processing purposes. One very important characteristic of the Fourier Transform is that given $F(u,v)$, it is possible to recover the spatial domain function, $f(x,y)$ [Russ 1999]. However, there have been numerous studies indicating that the use of the Fourier Transform for texture classification generally yields poor results [Jensen 1996].

3.5 Fractal Analysis

Classical Euclidean geometry stipulates that a line or curve is 1-dimensional, a plane is 2-dimensional and a cube is 3-dimensional. The integer dimension values 1, 2 and 3 are referred to as topological dimension, D_t . However, natural real-world forms are more spatially complex than simple topographic dimensions, thus leading to the concept of fractional (i.e. non-integer) dimension. First formulated by Hausdorff and Beiscovitch, Mandelbrot [1977, 1982] renamed the concept “fractal dimension” and defined fractals as “a set for which the Hausdorff-Beiscovitch dimension strictly exceeds the topological dimension.” With fractal geometry, a complex line (such as a contour line) will have fractal dimension somewhere between topological dimension 1 and 2, while a complex surface (such as a mountainous region) will have fractal dimension between 2 and 3 [Lam 1990].

The appeal of the fractal dimension is that it is not dependent upon the measurement scale and that it summarizes much of the roughness of surfaces in a way that seems to correspond to both the way nature works and the way humans perceive roughness [Russ 1999]. In surface roughness quantification, the fractal dimension can also be considered as a relative measure of the distribution of different-sized elements on the surface [Huang 1998].

Fractal dimension is based upon the concept of *self-similarity*, where a line or surface is composed of copies of itself that display increasing levels of detail at an enlarged scale [Jensen 1996]. Exact self-similarity may be illustrated using the “von Koch curve” (Figure 3.5).

Figure 3.5: The von Koch Curve

Line *A* represents the smallest segment. Curve *B* may be formed using 4 copies of Line *A*. Curve *C* may in turn be formed using copies of Curve *B* and so on to form Curves *D* and *E*.

Strictly speaking, there are no true (mathematical) fractals in nature [Baveye and Boast 1998]. However, objects in nature can exhibit statistical self-similarity over a finite area of interest or range of scales. This is referred to as *scale-invariance* or *self-affinity*.

A number of methods may be used to determine the fractal dimension of a line or surface including the calliper method, the transect method, the cell or box-counting method, power spectrum methods, approximation to Brownian motion, the blanket method, and others. An excellent overview of the various methods is provided online by Kenkel and Walker [1996].

3.6 Lacunarity

Lacunarity is a technique to evaluate the texture of images at multiple pattern scales. For the gliding box method developed by Allain and Cloitre [1991], the image must be first converted to binary (i.e. only contain 1's and 0's). Lacunarity is determined by passing a box of some initial dimension across the selected digital image. For each box size with given scale (ϵ), the number of black (foreground) pixels and white (background) pixels of the binary image are counted. As the box glides across the image, the mean (μ) number of black pixels per box is calculated (for that scale), as well as the standard deviation (σ). The coefficient of variation (CV) is then the ratio of σ to μ , with lacunarity calculated as the CV raised to the second power (Equation 3.7).

$$\Lambda_{\epsilon} = 1 + \left(\frac{\sigma}{\mu} \right)^2 \quad [3.7]$$

Where: Λ_ε is the average lacunarity at a given scale, ε
 μ is the mean number of black pixels per box
 σ is the standard deviation of black pixels per box

The size of the gliding box is then varied and the resulting lacunarity values are plotted against their respective box size (Figure 3.6a).

a) Lacunarity versus Box Size

b) Slope of Lacunarity versus Box Size

Figure 3.6: Lacunarity versus Box Size

The texture characteristics of a surface can be then described by observing inflection points in the lacunarity graph - i.e. points where there is a rapid change in slope. By plotting the slope of lacunarity against box size (Figure 3.6b), inflection points appear as troughs [Dale 2000].

When evaluating a trough in a lacunarity slope plot, the first feature to observe is its bottom – i.e. the actual point of slope inflection, which provides the average pattern size. The second feature of a trough to observe is its width. A narrow trough indicates discrete break points in the pattern while a wider trough indicates a more continuous transition in object sizes. With respect to an asphalt mix, the width of the trough could be used to determine whether or not the mix is gap-graded (i.e. the aggregate blend is dominated by a few discrete particle sizes) or densely graded (i.e. the aggregate blend consists of uniformly distributed aggregate sizes).

3.7 Overview of Three Dimensional Techniques

3.7.1 Introduction

So far, all of the techniques discussed are used to analyse 2-D representations of a 3-D surface. However, there are a number of data acquisition techniques that can provide accurate measurement of elevation data in addition to position data. Techniques for acquiring the third dimension may be broadly classified as either “passive” or “active.” In general, active techniques involve the projection of focussed electromagnetic energy such as laser light or ultrasonic waves onto a surface under investigation. In some cases, elevation data may be directly determined by measuring the time-of-flight of the projected pulse as in the case of lidar. Alternatively, a laser spot, line or grid may be projected upon a surface and subsequently imaged to observe its change in shape – a technique referred to as “structured light”.

Passive techniques involve imaging surfaces under natural or controlled lighting conditions that are already present in the scene. Depth information may be estimated from one image and its resulting shadows, known as shape-from-shading, or from multiple images such as stereo photogrammetry (multiple overlapping images under the same lighting conditions) or photometric stereo (multiple images of the same area under different lighting conditions).

There are various benefits and drawbacks of each technique. While time-of-flight ranging systems are the most costly, they involve the least amount of data processing. Passive systems requiring stereo images are the least expensive to construct, but require complex data processing.

At present, there are numerous active laser time-of-flight systems available for determining the macrotexture and roughness of pavement surfaces. These systems are expensive (up to \$80,000 for a single laser) and cannot collect microtexture information. As already described, the goal of this investigation was to develop a low-cost system to evaluate the frictional properties of pavement surfaces, which includes both macro and microtexture. As such, passive data collection systems were considered to be the most practical for this investigation. A brief overview of photogrammetry, shape-from-shading and photometric stereo is provided in the following sections.

3.7.2 Stereo Photogrammetry

When a point is imaged from two different viewpoints, its image projection undergoes a displacement from its position in the first image to that in the second image [Seitz 2003]. The amount of displacement, referred to as *parallax* or *optical flow*, is inversely proportional to the distance and may therefore be used to compute 3-D geometry using triangulation. The problem of establishing *correspondence* – i.e. matching the points (pixels) in one image to the other is a fundamental difficulty with this method.

In terms of image acquisition, there must be a balance between the distance between the two cameras (or the distance from a single camera's first and subsequent images) and the amount of overlap between the resulting stereo images. The further apart the cameras, the more accurate the disparity depth calculation [Zuech 2000], however, the smaller the amount of field-of-view overlap between images.

Once the stereo images are taken, the points in one image must be matched to the identical points in the second image. This problem, called "correspondence," is complicated because certain surfaces visible from one camera (or camera position) may not be visible in the second camera (or camera position) [Zuech 2000]. Also, lighting effects as viewed by one camera may result in the same surface having different characteristics in the two views (a feature that is capitalized upon in the photometric stereo technique). Correspondence is generally accomplished through the use of a least-squares matching procedure that seeks to minimize the sum of the squares of the difference in brightness level between the pixels of the two images.

3.7.3 Shape-From-Shading and Photometric Stereo

The shading of any point on a surface depends upon the surface reflection characteristics, surface geometry and lighting conditions under which the image was acquired. Therefore, given the pixel brightness values, can the shape of the surface be determined if the lighting conditions and the reflectance properties are known (or assumed)? The answer to this question was the subject of a PhD dissertation by Horn [1970], who pioneered the solution to this *Shape-From-Shading* (SFS) problem.

An excellent review of the progression of the SFS problem is provided by [Kim and Burger 1988]. They reflect that Horn provided solutions to the SFS problem by expressing it as a non-linear first order partial differential equation. It was assumed that the light source was far away so that the incident light rays were parallel and that the surface was smooth. The resulting

partial differential equation could be transformed to an equivalent set of five ordinary differential equations with respect to the surface parameter that varied with distance along a characteristic strip [Horn 1975]. Later, Horn introduced the *reflectance map* – also referred to as the *image irradiance equation*, which expresses the image intensity as a function of surface orientation in the gradient space [Horn 1977]. The reflectance map concept has been applied to many other practical fields such as automatic hill shading [Horn and Bachman 1978].

Another approach to the solution of the SFS problem is to use different light illumination conditions under which multiple images are generated from a fixed camera position. This technique is referred to the *Photometric Stereo Method* (PSM) [Kim and Burger 1988], first formulated by Woodham [1977]. To find the unique orientation of the surface, multiple images were taken using distant light sources with different incident light directions. If the surface is assumed to be purely Lambertian (i.e. diffuse), three images may be used to determine surface orientation uniquely. With non-Lambertian (specular, but uniform) surfaces, a series of look-up tables may be used [Silver 1980, Ikeuchi 1981]. Additional benefits of the PSM are that it produces easily implemented numerical methods, is somewhat free from noise of measured intensities and can be applied to textured surfaces [Kim and Burger 1988]. Indeed, more complex surfaces may also be included if images are illuminated from more than three directions.

Advancement of the PSM using point light sources has been conducted by Kim and Burger [1988, 1991]. The use of point light sources was of particular interest to this investigation, as the provision of distant light sources to project parallel light rays is not conducive to the construction of a portable imaging system for evaluating pavement specimens.

3.7.4 Depth from Texture Gradient

Texture gradient refers to the increasing fuzziness of visual texture with depth observed when viewing a 2-D image of a 3-D scene containing approximately uniformly textured planes or

objects [Zuech 2000]. Information concerning the surface slant and relative range may be determined by analyzing changes in texture “coarseness.” For a uniformly textured surface, the slant direction may be determined as the direction that the texture coarseness changes most rapidly, while an abrupt change in coarseness suggests an occluding edge. Successful use of this technique requires that the surface under investigation be highly textured (but uniformly so) and access to a powerful computer as the computational cost is high.

3.7.5 DEM Topographic Feature Analysis

Three dimensional surfaces may be replicated and modelled by computers using three different data structures – i) Triangulated Irregular Networks (TIN’s), ii) Grid-based surfaces, and iii) Contour lines. TIN’s are defined as a set of adjacent, non-overlapping contiguous triangles computed from irregularly spaced points (“mass” points) with x and y coordinates and z (elevation) values [Maune 2001]. TIN’s are particularly well suited for the calculation of slope, aspect and length, as well as volumetric cut/fill analysis, contour generation and interpolation.

Grid-based surfaces include digital elevation models (DEM’s), digital surface models (DSM’s) and digital terrain models (DTM’s). DEM’s usually represent bare earth elevations, whereas DTM’s may include additional elevation data for irregularly spaced features to better model the terrain. DSM’s model the elevations of top (reflective) surfaces such as trees or buildings.

As mentioned above, grid-based surfaces consist of a rectangular array of cells (such as pixels) that store an elevation value. The cells are uniform in area and are collected at regular intervals. The cell elevation values may be modelled in one of two ways. First, the elevation values may represent the surface elevation at the cell’s centroid, thus elevations between the various cell centroids (at the equivalent distance of the cell width) must be interpolated in some way, such as *kriging*. The second method assumes that the cell elevation is constant across its

entire area, thus changes in elevation occur only at cell boundaries. The first method more accurately models surfaces, but requires additional computation for interpolation.

Grid-based surfaces are readily analyzed using neighbourhood algorithms, but are less efficient than TIN's in terms of storage requirements as each cell must store an elevation value, whereas TIN's adapt to the variable complexity of the surface (i.e. less complexity results in fewer triangles) [Maune 2001]. Finally, contour lines are isolines that connect points on a 2-D image that have equal elevation.

Other visualization analyses may also be performed, including *hillshade* and *viewshed*. Hillshade involves the selection of a light source location and calculation of shaded areas from that selection to better view the surface terrain. Viewshed is also known as *intervisibility* or *line-of-sight* and is useful for determining the areas of surface that are visible from a selected viewpoint [Maune 2001].

3.7.6 Polynomial Texture Mapping

The type and direction of light source illuminating an object greatly affects the resulting image. An object that is illuminated from a particular distance and/or angle may look completely different when illuminated from a different distance/angle. Figure 3.7 displays an image of a cuniform tablet – an ancient clay tablet used for record keeping. As shown, under this lighting the right hand side of the tablet can be readily viewed and deciphered, however the left hand side shows less detail.

Consider the image in Figure 3.7 as a “map” consisting of static values of red, green and blue light. If these static values were replaced by functions that could change based on the position of the light source illuminating the object, then the map could be altered to highlight all areas of interest. Polynomial Texture Mapping (PTM) was developed at Hewlett Packard Limited by Dr. Thomas Malzbender (www.hpl.hp.com/ptm).

Figure 3.7: Ancient Cuneiform Tablet
(courtesy of Hewlett Packard Limited) – note that the right hand side of the tablet is much easier to view and decipher than the left under these lighting conditions.

The polynomial functions are interpolated by analyzing multiple images of the same object; each taken with a stationary camera under different lighting directions. A minimum of six different images is required, although at least ten images are recommended to provide redundancy in the calculations. Figure 3.8 shows a flow diagram of the PTM generation process. Viewer software allows the analyst to view the PTM under any light direction with a scroll of the mouse.

Figure 3.8: Polynomial Texture Mapping (PTM) Flow Diagram
(photo courtesy of Hewlett Packard Limited)

There are two particularly interesting features of PTM. First, the surface unit normal vectors (p, q, z) may be readily output from the viewing software. Second, surface detail may be enhanced by synthetically “relighting” the surface to maximize highlights. The cuniform tablet originally shown in Figure 3.7 is enhanced using PTM in Figure 3.9. As shown, the resulting image is considerably easier to view and decipher.

Figure 3.9: Synthetically Enhanced Cuniform Tablet Surface using PTM
(courtesy of Hewlett Packard Limited)

3.8 Recent Efforts to Estimate Friction and Macrotexture with Digital Analysis

3.8.1 Overview

When this investigation was initiated, no other research efforts to measure pavement friction and/or texture using digital image analysis techniques were underway. Over the past 8 years, other research groups have initiated their own investigations and a brief overview of their results to date are provided in the following sections.

3.8.2 Estimating Friction with Surface Normal Vectors

The use of surface normal vector images (developed using the Photometric Stereo Method) for predicting pavement friction as tested with the British Pendulum Test is underway at the Laboratoire Signal, Image et Communications (SIC) in France [Slimane et al. 2008]. To date, they have used surface normal vectors to extract relief information from the images with further analysis using an undisclosed “mixed criterion gradient/density” technique, with seemingly good correlation to BPN, although no coefficient of determination (R^2) values were provided. At present, they do not appear to have integrated a digital elevation model from the surface normal vector maps, and do not appear to be interested in macrotexture analysis.

3.8.3 Estimating Macrotexture with Digital Stereovision

Interestingly, other researchers have recently re-investigated digital stereovision techniques [de Leon Izeppi et al. 2008]. Successful generation of digital elevation models has been achieved, but only in the macrotexture range as the pixel dimensions are 0.5mm square. Good correlation between macrotexture depths calculated from the resulting DEMs and that measured with the Circular Texture Meter was reported.

3.8.4 Microtexture Profiling using Structured Light

Microtexture profile analysis has recently been investigated by Ergun et al. [2005] through the use of structured light – a technique whereby a sharp edge was used to cast a straight shadow line across a pavement surface at microscopic range. The root mean square deviation (R_q) and the average wavelength (L_a) of the microtexture profile were then correlated with coefficient of friction values at various speeds collected with an Odoliograph. While excellent correlation was observed (R^2 ranging from 0.89 to 0.968 depending upon surface type), the method is currently limited to the laboratory and is somewhat cumbersome. Furthermore, only a linear profile is investigated as opposed to an area-based analysis.

3.8.4 Estimating Macrotexture from Digital Elevation Models

Successful derivation of digital elevation models from surface normal vector maps appears to have been recently completed at the University of Manitoba by El-Gendy and Shalaby [2007]. The surface normal vector maps were generated from a 4-point photometric stereo arrangement and integration using a “global” technique. From the resulting DEMs, the researchers have focussed on the calculation of Mean Profile Depth (MPD) as per ASTM E1845 with very good correlation to manually measured profiles.

As with the digital stereovision effort of de Leon Izeppi et al. [2008], this research is limited to the macrotexture scale and the laboratory apparatus is too cumbersome for field use.

3.8.5 Novelty of Current Investigation

With respect to the other investigations discussed in this section, the current research effort provides a much more encompassing (or holistic) approach and therefore remains novel. It recognizes that both friction and texture measurements are required to characterize a pavement surface and therefore includes both the micro and macrotexture scales. It includes both laboratory and field components – recognizing that they cannot be mutually exclusive. Finally, both initial and in-service properties are investigated as pavements must provide adequate performance for many years.

CHAPTER 4: DIGITAL ANALYSIS OF SCHONFELD STEREOGRAPHS

4.1 Chapter Objective

The objective of Chapter 4 was to complete a proof-of-concept exercise to determine which of the analysis techniques discussed in Chapter 3 displayed the most promise for characterizing pavement friction and texture and which did not appear relevant. These results would be carried forward and guide the development of the new test device.

4.2 Relating Texture Code Number to Skid Number

The system developed by Schonfeld to classify pavement surface textures was introduced in Chapter 2. However, in addition to the classification system, Schonfeld went further to relate his texture parameters to locked wheel friction numbers (SN) at 48 and 96 km/h (30 and 60 mph). Data for this exercise were collected on various Ontario highways in 1967 consisting of thousands of skid measurements and thousands of stereographs [Schonfeld 1970].

Using the data, Schonfeld developed the “Table of Friction Weights”, which assigns a weighting to each texture parameter according to its contribution to pavement friction. The friction weight values vary according to the other texture parameters present in the Texture Code Number. For example, the friction weight for a high stone projection (Parameter A) is large when it is set against a smooth background (Parameter F), but is small if set against a harsh background (as its individual contribution to the overall friction would be reduced) [Schonfeld 1970]. The detailed procedure is not repeated herein, however, the actual skid trailer results obtained at 48 and 96 km/h (30 and 60 mph) were then plotted against their respective photo-interpreted values as shown in Figure 4.1a and b, respectively. As shown, very high correlation coefficients were obtained at both test speeds, indicating excellent estimation capability.

(a) Actual Skid Number vs. Interpreted Skid Number at 48 km/h (30 mph)

(b) Actual Skid Number vs. Interpreted Skid Number at 96 km/h (60 mph)

Figure 4.1: Actual Skid Number vs. Interpreted Skid Number
[from Schonfeld 1970 with permission from Ontario Ministry of Transportation]

In this manner, the Schonfeld system may be used to both estimate skid resistance in cases where actual skid testing cannot be completed (sharp turns or intersections), as well as for new surface materials at the mix design stage that have not yet been constructed. Indeed, Schonfeld [1970] suggests the following uses for the method:

- i) Selecting the most effective stone particle size, if the sand type and the polishing properties of rock and gravel are known,
- ii) Selecting the sand type to suit the coarse aggregate,
- iii) Finding the optimum height of relief if sharpness and harshness of the coarse aggregate and the sand type are known,
- iv) Selecting a suitable chip size and relief height for a pre-coated chipping surface (i.e. surface treatment or chip seal),
- v) Assessing the minimum depth of treatment of flushed asphalt pavements, and
- vi) Estimating the future decline or increase in skid resistance if the rock type of the aggregate is known.

The above may be considered as techniques for skid resistance mix design optimization, or troubleshooting existing pavements and will be of particular interest for this investigation. It should be mentioned that although these studies were completed in the 1970's the ASTM locked wheel friction trailer is still widely used in the United States, as well as by the MTO.

4.3 Early Automation of the Schonfeld Method

Based on the promising results achieved by Schonfeld, the Federal Highway Administration (FHWA) initiated a study to attempt to automate the photogrammetric process in order to reduce analysis time and remove human subjectivity [Howerter and Rudd 1976]. The selected stereographs were digitized and then algorithms were developed to yield information on particle width, height, angularity, and density in accordance with the Schonfeld method. The

information was then condensed into the six Schonfeld parameters and compared to the results manually obtained by Schonfeld. The results obtained during the automation project are shown in Table 4.1. As shown, the agreement between automatically and manually obtained results is reasonably good. The conclusions from the automation exercise were as follows:

- a) Pavement texture can be automatically classified in accordance with the Schonfeld method,
- b) The computer algorithms developed are capable of yielding more information than given by the Schonfeld method,
- c) With further research, it is likely that definitive relationships between pavement surface texture, skid resistance and/or tire noise may be developed,
- d) Although the automatic classification system developed is an excellent research tool, it may not be effective as an operational tool for large-scale inventory of pavement surface texture due to the off-line requirement for digitization of the stereographs and high cost associated with computer processing.

The conclusions of this early automation project are encouraging for further development. First, it has been shown that the Schonfeld method can be replicated automatically using digital analysis. Also, it was concluded that digital analysis of the stereographs could provide additional information concerning the surface than even the Schonfeld method provided – including the development of relationships between surface properties, friction and even noise. With specific reference to the final conclusion, the advent of digital imaging devices would allow the development of a system that does not require off-line digitization such that analysis may be completed in a fraction of the time required in the past.

Table 4.1: Early Automation of Schonfeld Method
(modified from Howerter and Rudd 1976 and with permission of TRB)

Sample	Method	Area Analyzed (mm ²)	Average Macrotexture Height		Average Macrotexture Width		Average Macro-texture Angularity		Macrotexture Density		Asperity Macrotexture Harshness		Background Macrotexture Harshness	
			Cate-gory	Value (mm)	Cate-gory	Value (mm)	Cate-gory	Value (mm)	Cate-gory	Value (%)	Cate-gory	Value	Cate-gory	Value
1	Manual	1000	3.6	1.61	2.1	2.89	2.1	n/a	3.4	85	3.2	n/a	0.0	n/a
	Auto	1440	3.5	1.477	1.3	5.131	1.6	1.050	2.3	57	2.3	n/a	4.4	n/a
		10979	3.6	1.6	1.3	5.184	1.8	0.924	2.3	57	2.3	n/a	4.1	n/a
2	Manual	1000	3.0	1.0	2.3	2.7	2.0	n/a	0.2	5	3.7	n/a	3.2	n/a
	Auto	1440	1.3	0.324	1.0	3.301	1.1	1.428	1.1	27.5	2.1	n/a	2.5	n/a
		10979	1.4	0.349	1.8	3.629	1.0	1.550	1.1	26.9	2.0	n/a	2.5	n/a
3	Manual	1000	3.5	1.49	2.0	3.0	2.1	n/a	0.8	19	2.8	n/a	2.8	n/a
	Auto	1440	2.1	0.571	1.9	3.357	1.4	1.200	1.1	26.1	2.1	n/a	2.6	n/a
		10455	2.1	0.566	1.6	4.275	1.4	1.203	1.0	24.9	n/a	n/a	2.7	n/a
4	Manual	1000	3.5	1.54	2.4	2.65	2.4	n/a	0.7	18	3.2	n/a	4.0	n/a
	Auto	1440	1.5	0.366	2.0	3.0	0.9	1.583	0.5	11.1	2.0	n/a	2.5	n/a
		1817	2.0	0.49	1.7	3.808	1.5	1.56	0.8	20.1	2.3	n/a	2.6	n/a
		9932	1.8	0.453	1.6	4.119	0.9	1.702	0.6	15.2	2.0	n/a	2.5	n/a

“Category” refers to the Schonfeld categories (all use the same scale) while “Value” represents the actual value where applicable

4.4 Data Availability

A visit to the Archives of Ontario revealed that a large number of the original stereographs taken by Schonfeld are still in existence, as well as their respective Schonfeld parameters and locked-wheel skid trailer data. A small number of stereographic prints of various pavement surfaces were obtained directly from the Ontario Ministry of Transportation (MTO), as well as the original Schonfeld parameter data. This smaller data set was used for the current research effort. Based on the results of the research, analysis of the slides held by the Archives of Ontario may be made in the future.

The Schonfeld stereographs provided by the Ontario Ministry of Transportation (MTO) are 250 by 250 mm black and white prints. As such, they were scanned at 300 dpi and converted to greyscale. As shown previously in Figure 2.12, the Schonfeld images contain the horizontal and vertical scales, as well as the project and location information.

Table 4.2 lists the highway sections for which Schonfeld images were available, as well as the respective SN values at 50 and 100 km/h. As shown, the SN values at 50 km/h ranged between 39 and 60, while the SN values at 100 km/h ranged between 26 and 43. Currently, the MTO considers an SN value of 30 (at the posted speed) as a threshold for further investigation. As Highway 401 is posted at 100 km/h, some of the values in Table 4.2 would merit further investigation and perhaps remedial effort from micro-milling, shotblasting, etc.

Table 4.2: Schonfeld Images Analyzed and Skid Numbers

Highway	Section	Skid Number at 50 km/h	Skid Number at 100 km/h
Highway 4 at North Elgin Road	2	55	39
	3	47	35
	4	60	42
	7	45	30
Highway 103 at Waubaushene	2	52	43
	3	48	39
	4	49	39
	5	48	38
	6	49	37
	7	49	37
	8	48	35
Highway 103 at Port Severn	1	49	38
	2	39	29
	3	49	36
	4	45	35
	5	45	34
	6	46	35
	7	45	36
	8	56	35
	9	43	32
Highway 6 at Wiarton North	2	43	26
	7	47	33
	10	48	33
Highway 11 at Holcroft Road	1	48	37
	2	48	38
	4	43	32
	8	47	39
Highway 11 at Highway 93	5	47	37
	6	44	35
	7	48	37

4.5 Two-Dimensional Analysis of Schonfeld Images

4.5.1 First Order Grey-Level Statistics

The analysis phase began by analyzing the left image of each of the Schonfeld stereo pairs in two dimensions. As the flash unit used by Schonfeld was located on the right side of the apparatus, the right images tend to be over-exposed when compared to the left images. As

initially reported in Goodman et al. [2005], the IDRISI Kilimanjaro software package developed by Clark Laboratories at Clark University in Massachusetts was used to calculate the minimum, maximum, mean, standard deviation and coefficient of variation for each of the following parameters were calculated for 30 images representing 6 different highway sections:

- i) Grey Level – the pixel brightness values ranging from 0 (black) to 255 (white).
- ii) Fractal Dimension – non-integer dimension exceeding topographical dimension (a measure of spatial complexity. Images of 3-dimensional surfaces typically yield fractal dimension between 2 and 3.
- iii) Aspect – the angular direction of maximum slope.
- iv) Slope – the slope of a pixel with reference to its surrounding neighbours.
- v) Diversity – how evenly individual cover types are distributed.
- vi) Dominance – the deviation from the maximum diversity.
- vii) Fragmentation – the number of different classes present in the analysis kernel with respect to the number of pixels in the analysis kernel.
- viii) Curvature – the second derivative of the partial quartic equation for a central pixel of a 3x3 kernel. Maximum curvature is the value associated with aspect, while minimum curvature is orthogonal to aspect.
- ix) Relative Richness – the number of cover types in the analysis kernel as a percentage of total number of classes in the image.

The image parameters that best correlated with their respective Schonfeld parameters and skid numbers at 50 and 100 km/h are shown in Table 4.3. Although the fractal dimension, curvature and slope measures displayed some promise, the resulting correlation coefficients (R) were quite poor, suggesting that these simple 2-dimensional texture measures are not sufficient to predict the Schonfeld parameters or the skid number directly.

Table 4.3: Results of 2-Dimensional Image Analysis

Schonfeld Parameter	Best Image Measure	Correlation Coeff. (R)
A - Macrotexture Height	Mean Minimum Curvature	0.50
	Maximum Fractal Dimension	-0.60
B - Macrotexture Width	Mean Minimum Curvature	0.51
	Mean Maximum Curvature	-0.52
C - Macrotexture Angularity	Mean Minimum Curvature	0.65
	SD of Minimum Curvature	-0.68
D - Macrotexture Density	Mean Maximum Curvature	0.49
	Mean Minimum Curvature	-0.48
E - Microtexture on Macro Projections	Mean Aspect	0.63
	Mean Minimum Curvature	-0.45
F - Background Microtexture	Mean Minimum Curvature	0.48
	Maximum Slope	-0.63
Skid Number at 30mph	Mean Fractal Dimension	0.59
	Mean Aspect	0.59
Skid Number at 60mph	Fractal Dimension Standard Deviation	-0.68
	Minimum Curvature Coeff. Of Variation	0.54
	Fractal Dimension Standard Deviation	-0.52

4.5.2 Second Order Grey-Level Statistics

As discussed in Section 3.3.3, a higher order of texture measures was proposed by Haralick [1979, 1986] based upon grey level co-occurrence matrices (GLCM) to account for the spatial dependency of brightness values. For this investigation, Angular Second Moment, Contrast, Entropy, Inverse Difference Moment, and Correlation were calculated and a correlation analysis conducted to determine whether the Schonfeld parameters or SN values were sensitive to changes in GLCM measures. The measures providing the greatest correlation with each parameter are presented in Table 4.4.

Table 4.4: Correlation Results for Grey Level Co-Occurrence Matrix Measures

Texture/Friction Parameter	Best Image Measure	Correlation Coefficient (R)
A – Macro-Projection Height	Contrast	-0.5
B – Macro-Projection Width	Inverse Difference Moment	0.49
C – Macro-Projection Angularity	Contrast	-0.65
D – Macro-Projection Density	Inverse Difference Moment	-0.49
E – Microtexture on Macro-Projections	Contrast	0.46
F – Background Microtexture	Contrast	-0.44
Skid Number at 50 km/h	Inverse Difference Moment	-0.53
	Contrast	0.52
Skid Number at 100 km/h	Inverse Difference Moment	-0.39
	Angular Second Moment	-0.39

As shown, Contrast and Inverse Difference Moment provided the greatest correlation with the Schonfeld parameters, although the coefficients (R) were low. As such, it did not appear that GLCM measures could be used to predict textural or friction properties.

4.5.3 Semivariance

Semivariance evaluation was completed using a freeware image analysis program called ImageJ, available online at <http://rsb.info.nih.gov/ij/>. The semivariance parameter was calculated for each row at lags ranging from 1 to 100 pixels and then averaged over all rows in the image. An example of the resulting semivariance curves for select Schonfeld images is presented in Figure 4.2.

Figure 4.2. Example Semivariance Curves for Schonfeld Images

Unfortunately, while the semivariance analysis provided interesting information concerning spatial dependence, no significant statistical correlation could be found between the semivariance parameters (Sill, Range, Nugget, etc.) and the Schonfeld parameters or the calculated SN.

4.5.4 Lacunarity

Lacunarity of the Schonfeld images was calculated using Image J with the FracLac plugin (<http://rsb.info.nih.gov/ij/plugins/frac-lac.html>). Prior to lacunarity calculation, the images were converted from greyscale to binary using the automatic histogram thresholding functionality of ImageJ. Lacunarity was calculated at a series of box sizes generally corresponding to standard aggregate sieve sizes used for mix design and production (Table 4.5). The Schonfeld images

included a measurement scale, so the actual size of each pixel was known (0.15mm). Due to the resolution of the scanned images, the 0.075mm sieve could not be represented.

Table 4.5: Lacunarity Box Size and Corresponding Aggregate Sieve Size

Box Size (pixels)	Aggregate Sieve Size (mm)
171	19
113	12.5
86	9.5
43	4.75
21	2.36
11	1.18
5	0.6
3	0.3
1	0.15

Figures 4.3 and 4.4 provide an example lacunarity and lacunarity slope plot, respectively for one of the six highway sections analyzed in this investigation. As shown, Images 2, 7 and 10 display flushing of increasing severity, respectively. Image 2 also displays a general lack of fine aggregate particles. Although detailed asphalt mix information was not available, the surface mix most commonly used in Ontario requires that all particles to be smaller than 19 mm, with a nominal maximum particle size of 12.5 mm.

The first area of interest in Figure 4.4 was from box size 1 to 171 (i.e. the individual particle sizes ranging from 0.111 to 19 mm), which displayed considerable difference between the three images. The second area of interest commenced at box size 171, where the curves converged with only minor deviation up to the maximum box size of 900, which was the size of the cropped Schonfeld images analyzed. Deviations between the three slope graphs above box size 171 (i.e. greater than 19 mm) suggested clumping of individual particles into larger groups. As such, lacunarity analysis may be useful for the evaluation of pavement surfaces for mix segregation during construction.

When evaluating a trough in a lacunarity slope plot, the first feature to observe is its bottom – i.e. the actual point of slope inflection, which provides the average pattern size. For Images 2 and 7 of Figure 4.4, the average aggregate size was therefore between 3.33 and 4.75 mm in diameter (box sizes 30 and 43). For Image 10 (displaying the least amount of visual flushing), however, the average aggregate size was between 2.0 and 2.36 mm in diameter (box sizes 18 and 21) likely because the flushed asphalt cement had not covered as many of the fine particles. Images from other highways evaluated (that did not display flushing) displayed troughs at smaller particle sizes – typically in the 0.222 to 1.0 mm range.

The second feature of a trough to observe is its width. A narrow trough indicates discrete break points in the pattern while a wider trough indicates a more continuous transition in object sizes. With respect to an asphalt mix, the width of the trough can be used to determine whether or not the mix is gap-graded (i.e. the aggregate blend is dominated by a few discrete particle sizes) or densely graded (i.e. the aggregate blend consists of uniformly distributed aggregate sizes). The actual gradations of the Schonfeld imaged mixes were not available for confirmation, however.

Although the lacunarity slope plots appeared to provide good information concerning the distribution of particle sizes, there was a further desire to quantitatively relate (and ultimately predict) the surface friction properties from one or more of the plotted features. As such, a series of correlation matrices were developed between the various features of the lacunarity plots, the Schonfeld texture parameters and the SN values at 50 and 100 km/h. Lacunarity features investigated included the actual lacunarity values themselves, values of the slope, values of curvature (the second derivative of lacunarity with respect to box size) and the area under the slope graph at different box sizes. Results are provided in Table 4.6.

Figure 4.3: Lacunarity versus Box Size for Asphalt Pavement Surface

Figure 4.4: Slope of Lacunarity versus Box Size for Asphalt Pavement Surface

Table 4.6: Correlation Results for Lacunarity Features

Texture/Friction Parameter	Best Measure	Correlation Coefficient (R)
A – Macro-Projection Height	Lacunarity Curvature between Boxes 7, 8 and 9 (Particle Sizes 0.78 to 1.0 mm)	-0.38
B – Macro-Projection Width	Lacunarity Slope between Boxes 30 and 43 (Particle Sizes 3.33 to 4.75)	-0.57
C – Macro-Projection Angularity	Lacunarity Curvature between Boxes 7, 8 and 9 (Particle Sizes 0.78 to 1.0 mm)	-0.54
D – Macro-Projection Density	Lacunarity Slope between Boxes 30 and 43 (Particle Sizes 3.33 to 4.75)	0.60
	Lacunarity Curvature between Boxes 7, 8 and 9 (Particle Sizes 0.78 to 1.0 mm)	0.61
E – Microtexture on Macro-Projections	Lacunarity Curvature between Boxes 7, 8 and 9 (Particle Sizes 0.78 to 1.0 mm)	0.46
	Lacunarity Slope between Boxes 2 and 3 (Particle sizes 0.22 to 0.33 mm)	-0.38
F – Background Microtexture	Lacunarity Curvature between Boxes 7, 8 and 9 (Particle Sizes 0.78 to 1.0 mm)	-0.47
	Lacunarity Slope between Boxes 2 and 3 (Particle sizes 0.22 to 0.33 mm)	0.34
Skid Number at 50 km/h	Lacunarity Curvature between Boxes 1, 2 and 3 (Particle Sizes 0.11 to 0.33 mm)	-0.70
Skid Number at 100 km/h	Lacunarity Slope between Boxes 90 and 100 (Particle Sizes 10 to 11.1 mm)	0.59

The correlation coefficients presented in Table 4.6 were not ideal, however, they confirmed some interesting relationships between texture and skid resistance. First, low correlation with Parameter A was anticipated, as macro-projection height is out of the 2D image plane.

Interestingly, Parameter B was best correlated with change in particle sizes between 3.33 to 4.75 mm, which traditionally would be considered part of the fine fraction of particles. However, only a portion of the coarse aggregate particles project outward from the reference

plane (much like an iceberg projecting from the water's surface) so the result was considered reasonable. The negative correlation coefficient suggests that a rapid change in particle size in this region results in decreasing particle width.

Although correlation was observed between the macro-projection angularity (Parameter C) and the change in slope (curvature), the relationship was negative and did not make intuitive sense. It is likely that additional analysis will be required to accurately measure angularity, such as the use of edge enhancing filters.

The density of macro-projection spacing was equally related to the change in smaller (0.78 to 1.0 mm) and larger (3.33 to 4.75 mm) particles, which made intuitive sense from a particle packing perspective.

The microtexture parameters (E and F) were correctly correlated with changes in the distribution of smaller particle sizes. Interestingly, correlation between Parameter E and F was negative, indicating that if the mixes investigated displayed increased microtexture on the macro-projections, they tended to have reduced background microtexture (and vice-versa).

The highest correlation was observed between the SN at 50 km/h and the change in particle sizes between 0.11 to 0.33 mm (i.e. the microtexture), while the SN at 100 km/h was most sensitive to changes in particle sizes between 10 and 11.1 mm (i.e. the macrotexture). This promising result supports the work of Krummer and Meyer (1967), who reported that the skid number at low speed is governed by microtexture while both micro and macrotexture are responsible for high-speed skid resistance.

4.6 Three-Dimensional Analysis of Schonfeld Images

The left and right images for select Schonfeld images were imported into the Orthoengine module of Geomatica with a series of ground elevation and tie-points then defined to assist the stereo matching process.

Unfortunately, no matter how many tie and/or ground elevation points were added, the software was unable to generate a DEM. This is in striking contrast to the original digital analysis effort by the FHWA (discussed in Section 4.2), that was able to derive the Schonfeld parameters from scanned images with good correlation. As the FHWA software, input parameters, and detailed analysis processes were not available for reference, effort to re-analyze the Schonfeld images in 3 dimensions was halted and development of a new digital imaging system commenced.

4.7 Summary of Proof of Concept Effort

As there are hundreds of techniques for analysing digital images, the goal of the investigation documented in Chapter 4 was to conduct a large number of analyses on a small (but representative) dataset to determine which techniques displayed the most potential for characterizing pavement friction and texture.

A sample of 30 Schonfeld images were digitized and subjected to various 1st order, 2nd order, semivariance and lacunarity analyses in two dimensions. The investigation was comprehensive, involving correlation analysis of 3180 data points, as outlined below:

Friction Data: 30 Imaged Areas * 2 Friction Values (each) = 60 data points

1st Order: 30 Images * 9 Measures * 5 Summary Statistics (each) = 1350 data points

2nd Order: 30 Images * 5 Measures = 150 data points

Semivariance: 30 Images * 4 Measures = 120 data points

Lacunarity: 30 Images * 50 Values = 1500 data points

With respect to the 1st order parameters, although the fractal dimension, curvature and slope measures displayed some promise, the resulting correlation coefficients (R) were quite poor, suggesting that these simple 2-dimensional texture measures are not sufficient to predict the Schonfeld parameters or the skid number directly. Likewise, the 2nd order analyses of semivariance and co-occurrence matrices did not produce better correlation.

Lacunarity analysis displayed the most promise for relating the change in pattern with scale to both the Schonfeld parameters directly, as well as the SN values. This analysis technique will therefore be carried forward for use with images collected with the newly developed imaging system, as well as friction and texture data collected during the field and laboratory phases of this investigation.

The Schonfeld images (as scanned) could not be successfully used to derive digital elevation models, so three-dimensional analysis was not conducted.

CHAPTER 5: DEVELOPMENT OF THE PAVEMENT SURFACE IMAGER

5.1 Chapter Objective

The objective of Chapter 5 is to discuss the considerations and thought process behind the design and construction of the new pavement surface imaging system, as well as modifications made as a result of initial testing.

5.2 Design Considerations

A major use of the Pavement Surface Imager (PSI) will be the evaluation of laboratory produced gyratory specimens during the asphalt mix design stage, as well as cores collected from the field during the quality control and assurance stage. The additional capability of evaluating in-service pavement surfaces – i.e. without the need for coring - was also an important design feature. The following general design criteria were considered:

- i) **Cost** – to promote widespread use of the PSI by contractors, consultants and government agencies, the cost of the device must be considerably less than existing test equipment. A target cost of between \$2,000 and \$5,000 was considered ideal.
- ii) **Ease of Operation** – the PSI must be designed so that it is simple to use by laboratory technicians with minimal training. Once the specimen has been inserted into the PSI, automated collection of the images, as well as the computer analysis was considered desirable to ensure consistency between different samples and reduce the potential for operator error. A reasonable analysis time (i.e. time required for computation) must also be considered.
- iii) **Size** – the PSI must be designed to fit on a standard table top for use in the laboratory, and must be portable for use in the field. A modular design was therefore anticipated.

- iv) **Robustness** – the overall design of the PSI, as well as the selected components, must be such to ensure a long and accurate service life for the end user.

5.3 Pavement Surface Imager Mark I

Based on a review of the literature, as well as due consideration for the design criteria, the design for the portable digital imaging system was initially based upon the photometric stereo method (PSM) arrangement suggested by Kim and Burger [1991] for a four-point light source system as shown in Figure 5.1 where S is any normalized distance. Utilizing this technique, it was hoped that both the elevation of each pixel and its respective surface orientation could be determined. The method developed by Kim and Burger [1991] was reportedly more efficient than other PSM analyses, which require the simultaneous solution of three non-linear equations (elevation, and two directional values for the surface normal vector) for each pixel. With the Kim and Burger technique, a single non-linear equation to determine pixel elevation is solved first with the resulting solution feeding into the additional equations for surface orientation.

The selection of the PSM over stereo photogrammetry may seem somewhat strange given the previous work of Schonfeld. However, with due consideration to the general design criteria, there were two main reasons for this choice as follows:

i) Single Imaging System with No Moving Parts

To produce the stereo images for 3-dimensional model development, stereo photogrammetry requires either the use of two imaging devices or the movement of a single imaging device between two viewpoints. The use of two imaging systems would increase the cost of the PSI, which was not desirable.

Figure 5.1: Non-Symmetrical Arrangement of Four Point Light Sources
[from Kim and Burger 1991]

Furthermore, as the unit will be used in an industrial environment, the use of moving parts (such as the moving a single imaging device for photogrammetry) is undesirable.

ii) No Correspondence Problems

The key to photogrammetry lies in the ability to match pixels between the two stereographs. This is called correspondence and is a relatively difficult task. The problem of correspondence was not an issue with Schonfeld's work, as human eyes are capable of automatically compensating for minor differences between stereo images and still construct the three-dimensional image. With digital correspondence, distinct and recognizable features are required in the images to promote accurate matching. A pavement surface is uniformly textured such that correspondence is difficult without the introduction of a significant number of tie-points or lines. In the case of PSM, the camera position is fixed and the resulting images are automatically registered [Kim and Burger 1988].

A photo of the Mark I unit is provided in Figure 5.2. The imaging system itself consists of a Nikon D70 digital single lens reflex (dSLR) camera with a resolution of 6 million pixels (3000 x 2000 pixels) fitted to a 60 mm fixed focal length macro lens. A particularly beneficial feature of the Nikon D70 camera is that the camera's functions are directly controlled via a laptop computer with the collected images transferred directly to the hard drive.

The wooden housing was sized for portability and provides a field of view of approximately 150 by 100 mm. Each pixel therefore covers an area of 0.05 by 0.05 mm. At this resolution, all of the macrotexture (approximately 0.5 to 19 mm for standard asphalt mixes) and a large portion of the microtexture (< 0.5mm) will be available for analysis.

In the laboratory arrangement shown in Figure 5.2, a lower support encasing a scissor jack system allows the core or gyratory specimen to be precisely aligned with the bottom of the housing (to preserve the standard field of view). To increase the microtexture resolution, an additional spacer was incorporated to reduce the field of view to approximately 90 by 60 mm, resulting in a pixel size of 0.03 by 0.03 mm.

The lighting system consists of four white 1-Watt light emitting diode (LED) bulbs mounted in the Kim and Burger configuration (Figure 5.1). A control pad was constructed to allow each light to operate independently (for collecting PSM images) or collectively for archiving purposes. The cost of the components for the Mark I unit was approximately \$2500.

5.3 Pavement Surface Imager Mark II

Six additional LED bulbs were added to allow the collection of additional images for PTM analysis (see Section 3.6.6). Figure 5.3 shows the relative locations of all LED bulbs on the Mark II unit. Incremental cost for the Mark II unit was approximately \$150 (components only).

Figure 5.2: Pavement Surface Imager Mark I

a) Plan View of Light Positions and Respective Illumination Fields

b) Front Elevation View of Light Positions

c) Side Elevation View of Light Positions

Figure 5.3: Light Locations for Surface Imager Mark II

CHAPTER 6: DATA COLLECTION

6.1 Chapter Objective

The objective of Chapter 6 is to detail the extensive laboratory and field data collection program completed during this investigation.

6.2 Field Sampling and Testing Program

6.2.1 Selection of Test Roads and Asphalt Mixes

A field sampling and testing program was developed within the standard sampling/testing regime conducted by the City of Ottawa during quality assurance evaluation. While additional sampling might have been beneficial, operational and financial constraints required that the sampling frequency be minimized – particularly to minimize the impact of destructive sampling on the performance of newly rehabilitated roads.

As per the City of Ottawa Special Provision F-3199 - End Result Specifications for Asphalt Concrete [City of Ottawa 2002], a paving project is sectioned into uniform lots – typically 500 m in length (single lane equivalent). For each lot, three samples of loose asphalt mix are taken to assess the actual asphalt cement content and gradation. Six compaction tests are also taken per lot (approximately once every 85 m) using 150 mm diameter cores to assess the as-constructed density of the mix. As the core specimens are not damaged during the density testing, they were made available for the imaging and friction/texture testing exercise.

Roads of interest were selected from the City of Ottawa Resurfacing Program as listed in Table 6.1 with codes assigned to the road name and contractor for privacy purposes. Projects with different traffic classifications (Table 6.2) and mix designs were selected to provide a broad sampling base.

Table 6.1: Test Roads Investigated and General Mix Information

Road Code	Asphalt Mix Type	Compactive Effort	PG Asphalt	Gradation	Contractor Code
POW	Superpave 12.5 mm FC1	100 gyrations	PG 64-34	Coarse, Dense Mix	RWT
H174	12.5 mm Stone Mastic Asphalt	75 gyrations	PG 70-34	Coarse, Open Mix	RWT
SLR	HL3	75 blows	PG 58-34	Fine, Dense Mix	KK
OCR	HL3	75 blows	PG 58-34	Fine, Dense Mix	KK
DR	HL3 with 3% MSM	75 blows	PG 58-34	Fine, Dense Mix	LNA
FD	HL3 with 3% MSM	75 blows	PG 58-28	Fine, Dense Mix	LNA
UDHS	Superpave 12.5 mm	50 gyrations	PG 58-34	Fine, Dense Mix	KK
UDH3	HL3	75 blows	PG 58-34	Fine, Dense Mix	KK
RR	HL1 Modified	75 blows	PG 64-34	Coarse, Dense Mix	RWT
FR	Type II Microsurfacing	n/a	n/a	Thin surfacing	MP

FC1 is Friction Coarse Type 1 and indicates that the coarse aggregate must have enhanced friction properties. HL1 and HL3 are dense-graded surface mixes designed using the Marshall method. HL1 uses enhanced friction aggregates. MSM is Manufactured Shingle Modifier.

Table 6.2: Traffic Data for Test Roads Investigated

Road Code	Asphalt Mix Type	2004 Average Annual Daily Traffic (Design Lane)	% Heavy Vehicles	20-Year Equivalent Single Axle Loads
POW	Superpave 12.5 mm FC1	2800	3.0	1.83 million
H174	12.5 mm SMA	24623	3.6*	16.1 million
SLR	HL3	739	5.5	0.75 million
OCR	HL3	429	2.6	0.20 million
DR	HL3 with 3% MSM	449	15.4	1.26 million
FD	HL3 with 3% MSM	480	6.5	0.57 million
UDHS	Superpave 12.5 mm	245	18.0	0.80 million
UDH3	HL3			
RR	HL1 Modified	2169	4.1	1.64 million
FR	Type II Microsurfacing	6140	9.5	10.64 million

*% Heavy Vehicles for H174 does not include buses, which have a dedicated transit lane.

As the City of Ottawa was in the middle of changing their asphalt mix design specifications from the Marshall Method (HL mixes) to Superpave, a selection of mixes designed with both systems was available for evaluation. In fact, Contractor KK decided to try both a standard Marshall mix (HL3) and a Superpave mix on the same project (UDH) as that was the first time they had attempted to produce Superpave mix.

Under the City's specifications, the HL1 Modified and Superpave FC1 mixes require the coarse aggregates to have enhanced friction properties. In Ottawa, this premium coarse aggregate material is usually produced from dolomitic sandstone, which is quite abrasive. HL3 and non-FC Superpave mixes are used for most Ottawa roads and are traditionally made with limestone aggregates. The SMA has 100% premium aggregates (not just the coarse fraction) and due to its gap-graded design has a much more open texture to reduce water splash and spray. The SMA is not a permeable mix, however, as it has high asphalt cement content. Type II microsurfacing also is produced with 100% premium aggregates, although this is a thin slurry treatment (± 10 mm in thickness) used to preserve the existing pavement and provide enhanced friction.

The aggregate gradations for each mix are presented in Figure 6.1 on a semi-log chart. For the dense-graded mixes (i.e. not the SMA), between the 9.5 and 0.300 mm sieves there is an eye-shaped gap separating the POW and RR mixes (lower lines) with the rest of the mixes (upper lines). In the early days of Superpave, this area was referred to as the "restricted zone" because mixes that incorporated rounded natural sands and went through this zone tended to be susceptible to permanent deformation. The restricted zone no longer applies to Superpave mixes, although it remains a good guide. Superpave now uses the primary control sieve concept to determine whether a mix is considered "fine" or "coarse" as identified in Table 6.1.

Figure 6.1: Gradation Bands of Asphalt Mixes Investigated

It should be mentioned that the specified gradation bands for HL1 and HL3 are virtually identical to the Superpave control points for 12.5 mm mixes. The gap-graded nature of the SMA is also immediately obvious in Figure 6.1, with 75% of the aggregate retained on the 4.75 mm sieve.

6.2.2 Field Macrotexture Testing

After the roads listed in Table 6.1 were paved, a Carleton University research team conducted macrotexture testing using an OPQ Spot-On laser texture sensor. This system incorporates a single dot laser to measure texture along a line and calculates Mean Profile Depth (MPD) as per ASTM E1845. The average values of MPD shortly after construction and at 1 year in service are presented in Table 6.3. As expected, the SMA mix (H174) had the greatest

macrotexture depth, followed by POW (coarse, dense-graded) and finally the fine, dense-graded mixes and microsurfacing (FR). High variation in the average MPD was observed for many of the mixes, particularly OCR and FD. Road RR was a later addition to the experiment and was not tested in the field.

Table 6.3: Mean Profile Depth of Test Sections

Road Code	Gradation	Mean Profile Depth (mm)			
		As Constructed		1-Year	
		Mean	COV	Mean	COV
POW	Coarse, Dense Mix	0.95	11.0%	1.13	13.5%
H174	Coarse, Open Mix	2.85	6.7%	2.92	7.6%
SLR	Fine, Dense Mix	0.64	14.1%	0.46	11.9%
OCR	Fine, Dense Mix	0.35	19.4%	0.50	13.9%
DR	Fine, Dense Mix	0.49	10.8%	0.51	13.7%
FD	Fine, Dense Mix	0.41	24.1%	0.53	17.2%
UDHS	Fine, Dense Mix	0.67	10.5%	0.63	12.6%
UDH3	Fine, Dense Mix	0.58	13.2%	0.57	7.1%
RR	Coarse, Dense Mix	Not tested			
FR	Thin surfacing	0.51	11.1%	0.48	9.8%

6.2.3 Field Friction Testing and Speed Correction Using IFI

At the same time as the field macrotexture testing, the Carleton University research team conducted friction testing using a Saab T-10 friction trailer to determine the wet coefficient of friction (μ) of the pavement surface. As introduced in Section 2.4.3, the T-10 trailer is a continuous measurement device that has been fitted with a patterned tire at 15% fixed slip. A calibrated spray system delivers a 0.5 mm film of water directly in front of the test wheel. The wet coefficient of friction values obtained after construction and at 1-year in service are provided

in Table 6.4. The typical test section length was 500 m, with measurements recorded at 10 m intervals.

Although the idea was to test the roads as quickly as possible after construction, in many cases this was not possible due to scheduling and communication issues. As such, the roads did experience some amount of trafficking (age provided in Table 6.4) before testing, whereas the laboratory samples were tested immediately after preparation.

Table 6.4: Field Friction Data from Test Roads

Road Code	Age at Test Date	Coefficient of Friction, μ			Age at Test Date	Coefficient of Friction, μ		
		Speed (km/h)	Mean	COV		Speed (km/h)	Mean	COV
POW	10-days	74.7	0.69	4.2%	1-Year	76.3	0.74	4.5%
H174	1-day	79.3	0.83	11.8%		87.4	0.78	4.2%
SLR	2-days	68.5	0.82	7.0%		65.6	0.70	4.5%
OCR	17-days	41.8	0.76	4.3%		49.2	0.73	6.1%
DR	6-days	78.4	0.63	3.9%		66.3	0.72	4.9%
FD	12-days	52.5	0.75	5.8%		42.9	0.70	9.0%
UDHS	9-days	78.3	0.78	3.1%		75.2	0.68	3.8%
UDH3	9 days	74.5	0.78	5.1%		49.9	0.76	6.2%
RR	Not tested					Not tested		
FR	47 days	84.9	0.76	6.9%		69.2	0.69	7.1%

The μ values provided in Table 6.4 required correction for testing speed to compare between individual road sections, as well as between the initial measurement and that taken after 1 year in service. This was done using the International Friction Index (IFI) process.

With reference to Equations 2.14 through 2.16, calibrated IFI model constants for the OPQ laser and Saab Friction Tester were not available at the time of the analysis. As such, model

constants from similar field devices were selected as provided in Table 6.5 (with the model constants for the sand patch test and British Pendulum).

The average “Golden” friction value at a slip speed of 60 km/h (F60) for each test section was then calculated using the friction and texture values from Tables 6.4 and 6.3, respectively. The estimated friction value at vehicle velocity 60 km/h (slip speed of 15%) was then determined to allow comparison between the individual mixes and testing periods (Table 6.6).

Table 6.5. International Friction Index Model Constants [PIARC 1995]

Measurement Device	Speed Number (Sp)		Friction Value at 60 km/h (F60) Constants			
	a	b	A	B	C	S
Sand Patch Test ⁽¹⁾	-11.6	113.6	n/a			
British Pendulum ⁽²⁾	n/a		0.07784	0.00709	0	10
Laser Texture Sensor ⁽³⁾	42.256	139.203	n/a			
Griptester ⁽⁴⁾	n/a		0.08209	0.9104	0	9.4

(1) Constants for PIARC Device ID “A8” – ASTM E-965 Sand Patch Test taken from Table 24 of [PIARC 1995]

(2) Constants for PIARC Device ID “A14” – US British Pendulum Test taken from Table 26 of [PIARC 1995] when macrotexture measure is MTD.

(3) Constants for PIARC Device ID “A4” at 72 km/h – CRR Mobile Profilometer taken Table 24 of [PIARC 1995]

(4) Constants for PIARC Device ID “D8” – Griptester taken from Table 25 of [PIARC 1995]

All else equal, friction has an inverse relationship with testing speed. As such, when adjusting mu values collected at vehicle speed in excess of the selected speed of 60 km/h, we would expect the mu values to increase because the testing speed is reduced. Indeed, using the model constants for the Griptester (which like the SFT uses a chain driven test wheel at low slip speed) and CRR Mobile Profilometer provided the correct adjustment and the results appear reasonable.

However, for roads that were tested at speeds below 60 km/h (OCR and FD at both the initial measurement and after 1-year, as well as UDH3 after 1 year in service), the process did not correctly reduce the mu values. For those roads, the original non-normalized values were

retained in Table 6.6. While perhaps not entirely precise, the normalized values in Table 6.6 may be used for comparative purposes.

Table 6.6: Field Friction Data from Test Roads Normalized to 60 km/h

Road Code	Age at Test Date	Coefficient of Friction, μ		Age at Test Date	Coefficient of Friction, μ	
		F60	μ at Test Speed of 60 km/h		F60	μ at Test Speed of 60 km/h
POW	10-days	0.55	0.75	1-Year	0.61	0.79
H174	1-day	0.76	0.86		0.72	0.81
SLR	2-days	0.59	0.88		0.48	0.78
OCR	17-days	0.46	0.76		0.50	0.73
DR	6-days	0.45	0.72		0.50	0.80
FD	12-days	0.48	0.75		0.48	0.70
UDHS	9-days	0.55	0.85		0.51	0.76
UDH3	9 days	0.57	0.84		0.53	0.76
RR	Not tested				Not tested	
FR	47 days	0.53	0.84		0.48	0.78

6.3 Laboratory Specimen Preparation and Testing Program

6.3.1 Gyratory Specimen Preparation and Quality Assurance Testing

Typical Marshall specimens in Ontario are only 100 mm in diameter and are therefore not suitable for British Pendulum testing as they do not provide sufficient surface area. Although 150 mm Marshall moulds could have been procured, all mixes were recompactd in the laboratory using the Superpave™ gyratory compactor to produce a circular surface with diameter of 150 mm.

Loose asphalt mix collected from multiple QA sublots was combined to provide enough mix for replicate gyratory specimens. As most of the mixes were not originally designed using

the gyratory compactor, the number of gyrations required to achieve 4 percent air voids was not known. HL3 is a general-purpose municipal surface mix for low to medium traffic volumes so 50 gyrations was used to compact the HL3 mixes, while 75 gyrations was used for the HL1 Modified mix. Three replicate gyratory specimens for each mix type were prepared.

Once cooled, the gyratory specimens were cut in half to allow testing of the top and bottom surface more readily. The bulk relative density (BRD) for each specimen (top and bottom specimen individually) was determined and used to calculate the BRD at each gyration. Numerous other constituent and volumetric properties were also determined, as presented in Tables 6.7, 6.8 and 6.9 for the core, gyratory bottom and gyratory top specimens, respectively with a description of the properties on the following pages:

- i) Pba – the mass percentage of asphalt cement added to the mixture by mass of aggregate.
- ii) Pb – the mass percentage of asphalt cement added to the mixture by mass of the total mixture.
- iii) Pbe – the effective mass percentage of asphalt cement added to the mixture by mass of total mixture, but not including the asphalt cement absorbed into the aggregate.
- iv) D60 – the sieve size opening at which 60% of the aggregate is retained.
- v) D30 – the sieve size opening at which 30% of the aggregate is retained.
- vi) D10 - the sieve size opening at which 10% of the aggregate is retained.
- vii) Cu – the coefficient of uniformity, calculated as the d60 divided by the d10.
- viii) Cc – the coefficient of curvature, calculated as the d30 squared divided by the product of the d10 and d60.

- ix) FM – the fineness modulus, calculated as the summation of the percentage of aggregate retained on each sieve between 0.15 and 9.5 mm divided by 100.
- x) BRD – the bulk relative density of the core or gyratory specimen in kg/m^3 .
- xi) Va – the percentage of air voids in the compacted mixture.
- xii) VMA – the voids in the mineral aggregate calculated as the summation of the percentage of air voids and volumetric percentage of asphalt cement in the compacted mixture.
- xiii) VFA – voids filled with asphalt calculated as the percentage of VMA filled with asphalt cement.
- xiv) DBR – the dust to binder ratio calculated as the mass percentage of material passing the 0.075 mm sieve over the mass percentage of asphalt cement (Pba).
- xv) MS-2 – the average asphalt cement film thickness (in microns) coating the aggregates in the mixture as determined by the Asphalt Institute Manual Series 2 procedure [1997] assuming that all particles are coated uniformly and equally.
- xvi) Idx – the average asphalt cement film thickness (in microns) coating the aggregates in the mixture as determined using the Index method proposed by Dr. Michael Heitzman of the Iowa Department of Transportation [Heitzman 2006]. The Index method allows the calculation of more realistic surface area values for each aggregate size based on the actual shape, volume and specific gravity of the particles.
- xvii) Virtual - the average asphalt cement film thickness (in microns) coating the aggregates in the mixture as determined using the Virtual method proposed by Dr. Michael Heitzman of the Iowa Department of Transportation [Heitzman 2006].

The Virtual method is a quasi-3-dimensional approach that can account for differences in compacted voids.

It is noteworthy that some of the specimens prepared in the gyratory compactor would not meet the City of Ottawa specifications for volumetric properties due to over- or under-compaction. The first three specimens (top and bottom) from RR were greatly over-compacted in the gyratory (to zero air voids), while the specimens from FD were under-compacted at the selected number of gyrations. These specimens were included to observe the affect of non-compliant volumetric properties upon friction and texture.

Table 6.7: Mix Properties from Quality Assurance Testing (Core Specimens)

Road	Specimen	Percent AC			Gradation Curve						Volumetrics					Film Thickness		
		Pba	Pb	Pbe	d60	d30	d10	Cu	Cc	FM	BRD	Va	VMA	VFA	DBR	MS-2	Idx	Virtual
POW	Core 1-1-1	4.00	3.8	2.98	7.0	2.2	0.25	28.0	2.8	4.928	2.320	6.5	17.0	62	0.8	4.82	9.64	14.7
	Core 1-1-3	4.61	4.4	3.54	5.5	1.7	0.25	22.0	2.0	4.642	2.316	6.9	17.6	61	0.7	5.60	11.1	14.8
	Core 1-1-4	4.73	4.5	3.65	6.0	1.8	0.27	22.2	2.0	4.754	2.286	8.3	18.8	56	0.7	5.93	11.7	14.5
	Core 1-1-5	4.61	4.4	3.54	5.5	1.7	0.26	21.2	2.0	4.642	2.332	6.4	17.0	62	0.7	5.60	11.0	14.7
	Core 1-1-6	4.61	4.4	3.54	5.5	1.7	0.26	21.2	2.0	4.642	2.345	5.9	16.6	64	0.7	5.60	11.0	14.8
H174	Core 1-2-1	5.88	5.6	4.66	9.0	5.3	0.15	60.0	21	5.332	2.258	7.2	19.7	64	1.1	5.98	15.8	18.4
	Core 1-2-3	5.56	5.3	4.37	9.5	5.7	0.18	52.8	19	5.458	2.237	8.1	20.3	60	0.9	6.28	14.9	18.4
	Core 1-2-4	5.63	5.3	4.43	8.6	5.1	0.15	57.3	20	5.255	2.236	8.1	20.3	60	1.2	5.36	14.9	17.5
	Core 1-3-1	5.61	5.3	4.41	8.8	5.2	0.13	67.7	24	5.245	2.253	7.1	19.7	64	1.3	5.05	14.9	17.8
	Core 1-3-2	5.88	5.6	4.66	8.3	5.1	0.15	55.3	21	5.236	2.275	6.2	19.1	68	1.1	5.73	15.7	18.9
SLR	Core 1-3-3	5.75	5.4	4.54	8.6	5.4	0.22	39.1	15	5.407	2.262	6.8	19.4	65	0.9	6.68	16.1	19.8
	Core 1	5.01	4.8	4.17	6.1	0.8	0.30	20.3	0.4	4.526	2.356	5.1	15.6	67	0.5	6.99	13.3	15.3
	Core 2	5.11	4.9	4.26	6.0	0.8	0.30	20.0	0.4	4.474	2.331	6.0	16.5	64	0.5	7.03	13.4	15.0
	Core 3	4.96	4.7	4.12	6.2	0.8	0.29	21.4	0.3	4.524	2.367	4.7	15.1	69	0.5	6.64	12.7	14.8
	Core 1	4.88	4.7	4.05	6.1	0.9	0.30	20.3	0.4	4.575	2.346	5.8	15.8	63	0.5	6.61	13.2	14.7
OCR	Core 2	5.11	4.9	4.26	6.5	0.7	0.28	23.2	0.3	4.379	2.348	4.9	15.9	69	0.6	6.12	12.2	14.8
	Core 3	4.92	4.7	4.09	6.3	0.8	0.30	21.0	0.4	4.566	2.340	5.7	16.0	64	0.5	6.51	13.0	14.9
	Core 1	5.09	4.8	3.93	4.9	0.4	0.15	32.7	0.2	3.926	2.417	4.1	16.5	75	1.0	3.80	8.7	13.0
DR	Core 2	5.24	5	4.07	4.7	0.4	0.15	31.3	0.3	3.882	2.408	4.7	17.0	72	1.1	3.80	8.7	12.4
	Core 3	5.24	5	4.07	4.8	0.4	0.16	30.0	0.2	3.934	2.410	4.8	17.0	72	1.0	3.85	8.8	12.3
	Core 1	4.65	4.4	3.65	4.3	0.3	0.16	26.9	0.1	3.853	2.254	10.3	20.5	50	0.9	3.53	8.4	10.5
FD	Core 2	4.49	4.3	3.50	4.1	0.5	0.21	19.5	0.3	3.978	2.263	10.6	20.1	47	0.9	4.00	9.5	11.3
	Core 3	4.29	4.1	3.32	3.6	0.5	0.18	20.0	0.3	3.816	2.247	10.8	20.5	47	1.0	3.45	8.4	10.9
	Core 1	5.01	4.8	4.17	5.0	0.7	0.27	18.5	0.4	4.299	2.321	6.3	16.8	63	0.6	6.18	11.9	13.8
UDH S	Core 2	4.80	4.6	3.98	5.7	0.8	0.30	19.0	0.4	4.457	2.318	6.4	16.7	62	0.5	6.35	12.2	14.4
	Core 3	5.07	4.8	4.22	5.6	0.9	0.29	19.3	0.5	4.484	2.311	6.7	17.2	61	0.6	6.59	12.8	14.3
	Core 4	5.07	4.8	4.22	5.5	0.9	0.29	19.0	0.5	4.484	2.256	8.9	19.2	54	0.6	6.59	12.8	13.8
UDH 3	Core 1	4.84	4.6	4.02	5.8	0.7	0.30	19.3	0.3	4.431	2.312	7.0	17.0	59	0.6	6.26	12.1	13.5
	Core 2	4.90	4.7	4.07	6.0	0.8	0.29	20.7	0.4	4.500	2.328	6.4	16.5	61	0.6	6.26	12.1	13.6
	Core 3	5.07	4.8	4.22	5.4	0.8	0.29	18.6	0.4	4.407	2.325	6.5	16.7	61	0.6	6.51	12.6	13.7

Table 6.7 Continued: Mix Properties from Quality Assurance Testing (Core Specimens)

Road	Specimen	Percent AC				Gradation Curve						Volumetrics					Film Thickness		
		Pba	Pb	Pbe		d60	d30	d10	Cu	Cc	FM	BRD	Va	VMA	VFA	DBR	MS-2	Idx	Virtual
RR	Core 1-1-1	5.54	5.2	4.41		5.5	1.3	0.23	23.9	1.3	4.552	2.285	7.8	18.7	58	0.6	6.67	13.2	14.4
	Core 1-1-2	5.47	5.2	4.34		6.4	1.7	0.26	24.6	1.7	4.780	2.393	4.0	14.8	73	0.6	7.12	13.9	16.0
	Core 1-1-3	5.76	5.4	4.60		5.5	1.6	0.26	21.2	1.8	4.632	2.335	6.3	17.1	63	0.6	7.34	14.4	15.0
	Core 1-1-4	5.76	5.4	4.60		5.5	1.6	0.26	21.2	1.8	4.632	2.320	6.9	17.6	61	0.6	7.34	14.4	14.8
	Core 1-2-1	5.39	5.1	4.27		6.0	1.5	0.16	37.5	2.3	4.638	2.374	4.7	15.4	69	0.6	6.80	13.3	15.3
	Core 1-2-2	5.58	5.3	4.44		5.8	1.6	0.25	23.2	1.8	4.671	2.350	5.7	16.4	65	0.6	7.10	13.9	15.1

Table 6.8: Mix Properties from Quality Assurance Testing (Gyratory Bottom Specimens)

Road	Specimen	Percent AC				Volumetric Properties								Gradation Curve					Film Thickness			
		Pb	Pba	Pbe	N	Va	BRD	MRD	VMA	VFA	DBR	2.36	FM	Cu	Cc	MS-2	Idx	Virtual				
POW	1B	4.4	4.6	3.54	100	2.5	2.444	2.506	13.1	81	0.7	36.9	4.6	22	1.98	5.60	11.0	16.2				
	2B	4.4	4.6	3.54	100	2.6	2.441	2.506	13.2	80	0.7	36.9	4.6	22	1.98	5.60	11.0	16.1				
	3B	4.4	4.6	3.54	100	2.5	2.444	2.506	13.1	81	0.7	36.9	4.6	22	1.98	5.60	11.0	16.2				
H174	1B	5.3	5.6	4.40	75	1.1	2.415	2.441	13.9	92	0.9	21.8	5.2	67.7	23.6	5.04	14.8	23.1				
	2B	5.6	5.9	4.67	75	2.6	2.377	2.441	15.5	83	1.1	20.8	5.3	58.7	20.5	5.88	15.8	20.9				
	3B	5.6	5.9	4.67	75	1.2	2.412	2.441	14.2	92	1.1	20.8	5.3	58.7	20.5	5.88	15.8	23.7				
	4B	5.6	5.9	4.67	50	2.4	2.383	2.441	15.3	84	1.1	20.8	5.3	58.7	20.5	5.88	15.8	21.3				
	5B	5.6	5.9	4.67	50	2.5	2.381	2.441	15.3	84	1.1	20.8	5.3	58.7	20.5	5.88	15.8	21.2				
	6B	5.6	5.9	4.67	50	2.7	2.376	2.441	15.5	83	1.1	20.8	5.3	58.7	20.5	5.88	15.8	20.9				
SLR	1B	4.9	5.1	4.25	50	4.2	2.375	2.478	14.9	72	0.5	41.7	4.5	20	0.37	7.08	13.5	16.0				
	2B	4.9	5.1	4.25	50	4.8	2.358	2.478	15.5	69	0.5	41.7	4.5	20	0.37	7.08	13.5	15.7				
OCR	1B	4.8	4.9	4.07	50	5.2	2.349	2.479	15.7	67	0.6	43.6	4.4	20.7	0.35	6.01	12.0	14.3				
DR	1B	4.8	5	3.85	50	4.2	2.427	2.532	16.2	74	1.0	50.4	3.9	29.4	0.25	3.71	8.5	12.5				
	2B	4.8	5	3.85	50	4.4	2.421	2.532	16.4	73	1.0	50.4	3.9	29.4	0.25	3.71	8.5	12.4				
	3B	4.8	5	3.85	50	4.1	2.428	2.532	16.1	75	1.0	50.4	3.9	29.4	0.25	3.71	8.5	12.5				
FD	1B	4.1	4.3	3.33	50	7.6	2.326	2.516	17.7	57	0.9	50.8	4.0	24.4	0.28	3.54	8.6	11.6				
	2B	4.1	4.3	3.33	50	7.8	2.321	2.516	17.9	57	0.9	50.8	4.0	24.4	0.28	3.54	8.6	11.6				
	3B	4.1	4.3	3.33	50	8.0	2.316	2.516	18.1	56	0.9	50.8	4.0	24.4	0.28	3.54	8.6	11.6				

Table 6.8 Continued: Mix Properties from QA Testing (Gyratory Bottom Specimens)

Road	Specimen	Percent AC			Volumetric Properties							Gradation Curve				Film Thickness		
		Pb	Pba	Pbe	N	Va	BRD	MRD	VMA	VFA	DBR	2.36	FM	Cu	Cc	MS-2	Idx	Virtual
UDH S	1B	4.8	5	4.16	50	4.1	2.366	2.467	15.2	73	0.6	43.5	4.4	19.6	0.38	6.43	12.8	15.7
	2B	4.8	5	4.16	50	4.3	2.36	2.467	15.4	72	0.6	43.5	4.4	19.6	0.38	6.43	12.8	15.6
	3B	4.8	5	4.16	50	4.2	2.363	2.467	15.3	72	0.6	43.5	4.4	19.6	0.38	6.43	12.8	15.6
RR	1B	5.2	5.5	4.37	75	0	2.463	2.457	12.3	102	0.7	36.1	4.8	25.2	1.8	6.87	13.5	40.9
	2B	5.2	5.5	4.37	75	0	2.46	2.457	12.4	101	0.7	36.1	4.8	25.2	1.8	6.87	13.5	41.3
	3B	5.2	5.5	4.37	75	0	2.462	2.457	12.4	102	0.7	36.1	4.8	25.2	1.8	6.87	13.5	41.0
	4B	5.1	5.4	4.28	50	1.9	2.423	2.471	13.7	86	0.6	35.0	4.8	23.3	1.7	7.21	14.1	19.6
	5B	5.1	5.4	4.28	50	1.8	2.426	2.471	13.6	87	0.6	35.0	4.8	23.3	1.7	7.21	14.1	19.8
	6B	5.1	5.4	4.28	50	2.4	2.413	2.471	14.0	83	0.6	35.0	4.8	23.3	1.7	7.21	14.1	19.0
	7B	5.1	5.4	4.28	35	3.9	2.375	2.471	15.4	75	0.6	35.0	4.8	23.3	1.7	7.21	14.1	17.5

Table 6.9: Mix Properties from Quality Assurance Testing (Gyratory Top Specimens)

Road	Specime n	Percent AC			Volumetric Properties							Gradation Curve				Film Thickness		
		Pb	Pba	Pbe	N	Va	BRD	MRD	VMA	VFA	DBR	2.36	FM	Cu	Cc	MS-2	Idx	Virtual
POW	1T	4.4	4.6	3.54	100	3.4	2.42	2.506	13.9	75	0.7	36.9	4.6	22	1.98	5.60	11.0	26.7
	2T	4.4	4.6	3.54	100	3.4	2.421	2.506	13.9	76	0.7	36.9	4.6	22	1.98	5.60	11.0	26.8
	3T	4.4	4.6	3.54	100	3.4	2.421	2.506	13.9	76	0.7	36.9	4.6	22	1.98	5.60	11.0	26.8
H174	1T	5.3	5.6	4.40	75	0.9	2.418	2.441	13.8	93	0.9	21.8	5.2	67.7	23.6	5.88	14.8	57.7
	2T	5.6	5.9	4.67	75	4.6	2.33	2.441	17.2	74	1.1	20.8	5.3	58.7	20.5	5.88	15.8	45.8
	3T	5.6	5.9	4.67	75	1.8	2.396	2.441	14.8	88	1.1	20.8	5.3	58.7	20.5	5.88	15.8	52.8
	4T	5.6	5.9	4.67	50	3.0	2.367	2.441	15.8	81	1.1	20.8	5.3	58.7	20.5	5.88	15.8	48.8
	5T	5.6	5.9	4.67	50	3.7	2.352	2.441	16.4	78	1.1	20.8	5.3	58.7	20.5	5.88	15.8	47.4
SLR	6T	5.6	5.9	4.67	50	3.7	2.35	2.441	16.5	77	1.1	20.8	5.3	58.7	20.5	5.88	15.8	47.2
	1T	4.9	5.1	4.25	50	5.4	2.345	2.478	16.0	66	0.5	41.7	4.5	20	0.37	7.08	13.5	23.5
	2T	4.9	5.1	4.25	50	5.2	2.349	2.478	15.9	67	0.5	41.7	4.5	20	0.37	7.08	13.5	23.6
	3T	4.9	5.1	4.25	50	5.0	2.353	2.478	15.7	68	0.5	41.7	4.5	20	0.37	7.08	13.5	23.7

Table 6.9 Continued: Mix Properties from QA Testing (Gyratory Top Specimens)

Road	Specime n	Percent AC			Volumetric Properties							Gradation Curve				Film Thickness		
		Pb	Pba	Pbe	N	Va	BRD	MRD	VMA	VFA	DBR	2.36	FM	Cu	Cc	MS-2	Idx	Virtual
OCR	1T	4.7	4.9	4.07	50	5.4	2.345	2.479	15.8	66	0.6	43.6	4.4	20.7	0.35	6.01	12.0	22.7
	1T	4.8	5	3.85	50	5.4	2.396	2.532	17.2	69	1.0	50.4	3.9	29.4	0.25	3.71	8.5	17.9
	2T	4.8	5	3.85	50	5.3	2.399	2.532	17.1	69	1.0	50.4	3.9	29.4	0.25	3.71	8.5	17.9
	3T	4.8	5	3.85	50	5.0	2.405	2.532	16.9	70	1.0	50.4	3.9	29.4	0.25	3.71	8.5	18.1
FD	1T	4.1	4.3	3.33	50	8.2	2.31	2.516	18.3	55	0.9	50.8	4.0	24.4	0.28	3.54	8.6	16.0
	2T	4.1	4.3	3.33	50	8.4	2.306	2.516	18.4	55	0.9	50.8	4.0	24.4	0.28	3.54	8.6	15.9
	3T	4.1	4.3	3.33	50	8.0	2.315	2.516	18.1	56	0.9	50.8	4.0	24.4	0.28	3.54	8.6	16.0
	1T	4.8	5	4.16	50	4.8	2.349	2.467	15.8	70	0.6	43.5	4.4	19.6	0.38	6.43	12.8	24.6
UDH S	2T	4.8	5	4.16	50	5.0	2.345	2.467	15.9	69	0.6	43.5	4.4	19.6	0.38	6.43	12.8	24.5
	3T	4.8	5	4.16	50	4.3	2.362	2.467	15.3	72	0.6	43.5	4.4	19.6	0.38	6.43	12.8	25.0
	1T	5.2	5.5	4.37	75	0.3	2.45	2.457	12.8	98	0.7	36.1	4.8	25.2	1.83	6.87	13.5	48.3
	2T	5.2	5.5	4.37	75	0.3	2.449	2.457	12.8	97	0.7	36.1	4.8	25.2	1.83	6.87	13.5	47.4
RR	3T	5.2	5.5	4.37	75	0.5	2.446	2.457	12.9	97	0.7	36.1	4.8	25.2	1.83	6.87	13.5	45.4
	4T	5.1	5.4	4.28	50	2.6	2.407	2.471	14.2	82	0.6	35.0	4.8	23.3	1.7	7.21	14.1	33.0
	5T	5.1	5.4	4.28	50	2.4	2.413	2.471	14.0	83	0.6	35.0	4.8	23.3	1.7	7.21	14.1	33.6
	6T	5.1	5.4	4.28	50	3.0	2.396	2.471	14.6	79	0.6	35.0	4.8	23.3	1.7	7.21	14.1	32.2
	7T	5.1	5.4	4.28	35	4.3	2.366	2.471	15.7	73	0.6	35.0	4.8	23.3	1.7	7.21	14.1	30.5

6.3.2 Sand Patch Testing

Sand patch testing (Figure 6.2) was conducted on the core, gyratory top and gyratory bottom surfaces according to ASTM E965-2001 to determine the Mean Texture Depth (MTD) as presented in Table 6.10 for the core specimens and Table 6.11 for the gyratory specimens. Detailed data is provided in Appendix 1. As the surface of Road FR was microsurfacing, no gyratory specimens could be produced. Furthermore, Specimens SLR 3 (Bottom), OCR 2 (Bottom and Top), and OCR 3 (Top) could not be tested as the paper discs inserted into the gyratory mould during preparation could not be removed completely and therefore blocked some of the texture.

As anticipated, the gap-graded H174 cores produced the greatest average macrotexture depth (1.60 mm), followed by the coarse-graded cores POW and RR having MTD values of 0.51 and 0.47 mm, respectively. The fine-graded cores ranged from 0.24 to 0.30 mm, while the microsurfacing specimen had an MTD value of 0.32 mm.

Figure 6.2: Sand Patch Testing of Core Specimens

Table 6.10: Mean Texture Depth (MTD) of Core Specimens

Project	Specimen	Mean Texture Depth (mm)	Average Mean Texture Depth (mm)
POW	Core 1-1-1	0.52	0.51
	Core 1-1-3	0.51	
	Core 1-1-4	0.54	
	Core 1-1-5	0.49	
	Core 1-1-6	0.50	
H174	Core 1-2-1	1.62	1.60
	Core 1-2-3	1.74	
	Core 1-2-4	1.89	
	Core 1-3-1	1.43	
	Core 1-3-2	1.43	
	Core 1-3-3	1.48	
SLR	Core 1	0.32	0.30
	Core 2	0.31	
	Core 3	0.27	
OCR	Core 1	0.23	0.24
	Core 2	0.25	
	Core 3	0.23	
DR	Core 1	0.25	0.29
	Core 2	0.30	
	Core 3	0.31	
FD	Core 1	0.25	0.24
	Core 2	0.24	
	Core 3	0.25	
UDHS	Core 1	0.37	0.30
	Core 2	0.28	
	Core 3	0.25	
	Core 4	0.29	
UDH3	Core 1	0.33	0.29
	Core 2	0.27	
	Core 3	0.25	
RR	Core 1-1-1	0.57	0.47
	Core 1-1-2	0.40	
	Core 1-1-3	0.48	
	Core 1-1-4	0.41	
	Core 1-2-1	0.49	
	Core 1-2-2	0.43	
FR	Core 1	0.37	0.32
	Core 2	0.29	
	Core 3	0.29	

Table 6.11: Mean Texture Depth (MTD) of Gyratory Specimens

Road	Specimen	Mean Texture Depth (mm)			
		Bottom Surface		Top Surface	
		Value	Average	Value	Average
POW	1	0.49	0.51	0.66	0.80
	2	0.52		0.83	
	3	0.52		0.90	
H174	1	0.75	1.09	1.12	1.57
	2	1.13		1.68	
	3	0.89		1.53	
	4	1.09		1.41	
	5	1.32		1.87	
	6	1.35		1.83	
SLR	1	0.46	0.45	0.46	0.47
	2	0.45		0.44	
	3	Not tested		0.49	
OCR	1	0.56	0.56	0.49	0.49
	3	0.55		Not tested	
DR	1	0.24	0.22	0.31	0.34
	2	0.22		0.32	
	3	0.21		0.38	
FD	1	0.27	0.27	0.38	0.39
	2	0.26		0.41	
	3	0.28		0.38	
UDHS	1	0.41	0.38	0.67	0.59
	2	0.38		0.55	
	3	0.35		0.56	
RR	1	0.41	0.50	0.74	0.74
	2	0.45		0.70	
	3	0.41		0.71	
	4	0.54		0.70	
	5	0.57		0.78	
	6	0.54		0.74	
	7	0.57		0.77	

With one exception (OCR), the gyratory top surfaces consistently yielded greater MTD than the bottom surfaces although the bottom surfaces yielded greater MTD than the core specimens. As with the core specimens, the gap-graded H174 specimens had the greatest MTD, followed by the coarse-graded and fine-graded mixes, respectively.

6.3.3 British Pendulum Testing and Specimen Polishing

British Pendulum testing was completed according to ASTM E303. The specimens were held horizontally in a custom-built testing platform and vice apparatus as shown in Figure 6.3. The apparatus ensured that the specimen was properly centred with respect to the path of the test shoe and a bubble level was used to ensure that the specimen was horizontal before testing. A spray bottle was used to wet the surface of each sample and an infrared thermometer was used to measure the surface temperature during each test. The amount of water sprayed on the surface was kept as constant as possible, however as per Csathy [1963], simply wiping the surface of an asphalt pavement with a damp cloth provides up to 85 to 90% of the expected reduction in BPN.

The surfaces of all specimens were first tested with the British Pendulum in the “as-constructed” or “as-prepared” condition, referred to as the Unpolished state.

Polishing effort was then imposed upon the specimen surfaces using a manual hand sander approximately 225 mm long and 75 mm in width wrapped with 60-grit sandpaper, which appeared to effectively remove the asphalt cement film with few polishing cycles. One cycle of polishing was counted when the hand sander was moved up and back across the surface in the direction parallel with the travel of the British Pendulum shoe. British Pendulum testing was repeated on the specimen surfaces after 10, 30 and 80 polishing cycles referred to as the Low, Medium and High states of polish, respectively. The selection of 10, 30 and 80 polishing cycles was based on evaluation of a limited number of trial specimens that suggested maximum friction would be obtained at 10 polish cycles followed by a decline in friction with 30 and 80 cycles. The detailed BPN data is also provided in Appendix 1.

The temperature corrected BPN values are provided in Table 6.12 for all states of polish.

Figure 6.3: British Pendulum Platform and Specimen Vice
(inset shows top view of specimen vice and bubble level)

Table 6.12: Temperature Corrected British Pendulum Numbers at Four States of Polish

Road	Specimen	No Polishing Effort	Low Polishing (10 cycles)	Medium Polishing (30 cycles)	High Polishing (80 cycles)
		BPN	BPN	BPN	BPN
POW	Core 1-1-1	62.7	64.6	66.6	60.6
	Core 1-1-3	61.4	65.8	67.1	61.4
	Core 1-1-4	55.9	59.0	63.1	59.7
	Core 1-1-5	58.2	59.7	70.0	64.7
	Core 1-1-6	56.9	60.8	65.1	60.9
	Gyratory 1 - Bottom	62.1	63.9	66.5	63.3
	Gyratory 1 - Top	72.4	66.4	68.8	67.6
	Gyratory 2 - Bottom	57.6	59.9	66.0	60.4
	Gyratory 2 - Top	72.2	68.7	76.1	67.3
	Gyratory 3 - Bottom	60.1	62.7	66.1	60.0
	Gyratory 3 - Top	72.6	68.4	70.9	65.4
H174	Core 1-2-1	47.7	60.5	52.2	55.7
	Core 1-2-3	53.4	62.3	57.2	57.1
	Core 1-2-4	52.1	54.3	53.3	47.9
	Core 1-3-1	47.4	54.5	51.9	51.6
	Core 1-3-2	46.2	55.0	47.3	49.5
	Core 1-3-3	37.0	60.9	53.4	52.2
	Gyratory 1 - Bottom	67.5	64.5	55.5	61.9
	Gyratory 1 - Top	66.6	71.7	64.6	66.1
	Gyratory 2 - Bottom	71.5	74.5	61.2	71.1
	Gyratory 2 - Top	63.2	69.7	61.0	67.3
	Gyratory 3 - Bottom	71.7	72.5	64.5	69.5
	Gyratory 3 - Top	69.0	69.8	67.9	66.0
	Gyratory 4 - Bottom	72.1	67.7	68.3	68.0
	Gyratory 4 - Top	66.7	74.8	67.0	72.7
	Gyratory 5 - Bottom	72.2	70.6	66.7	60.2
	Gyratory 5 - Top	70.0	74.3	67.7	69.1
	Gyratory 6 - Bottom	67.2	73.4	66.5	61.5
	Gyratory 6 - Top	70.9	74.1	67.0	67.1
SLR	Core 1	59.9	65.4	60.5	60.2
	Core 2	57.0	61.4	60.2	58.5
	Core 3	60.0	67.1	66.3	57.5
	Gyratory 1 - Bottom	57.7	62.7	66.5	62.4
	Gyratory 1 - Top	62.4	65.2	70.5	60.6
	Gyratory 2 - Bottom	63.0	63.2	60.2	62.7
	Gyratory 2 - Top	65.9	66.2	70.0	63.5
	Gyratory 3 - Top	62.1	69.4	69.7	62.5

Table 6.12 Continued: British Pendulum Numbers at Four States of Polish

Road	Specimen	No Polishing Effort	Low Polishing (10 cycles)	Medium Polishing (30 cycles)	High Polishing (80 cycles)
		BPN	BPN	BPN	BPN
OCR	Core 1	58.2	73.9	64.2	58.9
	Core 2	59.5	71.1	66.5	60.5
	Core 3	56.9	70.1	63.5	61.3
	Gyratory 1 - Bottom	69.1	69.2	68.2	58.9
	Gyratory 1 - Top	72.4	71.9	66.9	60.5
DR	Core 1	68.7	70.3	62.5	55.4
	Core 2	68.4	70.6	65.9	61.9
	Core 3	68.5	70.2	64.7	57.8
	Gyratory 1 - Bottom	66.5	72.4	55.2	55.9
	Gyratory 1 - Top	67.1	75.0	61.4	57.6
	Gyratory 2 - Bottom	67.7	69.3	59.1	51.4
	Gyratory 2 - Top	69.1	69.3	62.1	54.8
	Gyratory 3 - Bottom	66.1	67.4	61.9	50.9
	Gyratory 3 - Top	72.4	69.4	63.6	57.0
FD	Core 1	58.7	70.4	67.7	66.0
	Core 2	62.2	72.6	67.6	65.2
	Core 3	64.2	71.6	67.6	63.9
	Gyratory 1 - Bottom	67.4	74.9	66.5	68.8
	Gyratory 1 - Top	72.2	72.7	67.1	70.5
	Gyratory 2 - Bottom	70.0	71.5	70.7	66.7
	Gyratory 2 - Top	73.9	73.8	69.7	68.3
	Gyratory 3 - Bottom	63.6	74.5	73.8	70.5
	Gyratory 3 - Top	68.5	71.2	66.6	69.8
UDH3	Core 1	64.4	72.9	69.6	70.0
	Core 2	58.7	68.9	67.4	66.1
	Core 3	60.5	69.4	66.2	66.0
UDHS	Core 1	60.7	65.8	68.2	72.2
	Core 2	59.9	69.9	68.2	66.6
	Core 3	59.1	69.3	67.6	66.6
	Core 4	59.1	67.3	65.9	69.5
	Gyratory 1 - Bottom	64.2	70.7	65.0	65.3
	Gyratory 1 - Top	68.9	69.4	66.6	66.0
	Gyratory 2 - Bottom	63.0	70.7	64.8	61.6
	Gyratory 2 - Top	72.1	71.7	66.2	66.8
	Gyratory 3 - Bottom	64.9	66.8	63.7	62.5
	Gyratory 3 - Top	70.0	72.4	65.5	65.5

Table 6.12 Continued: British Pendulum Numbers at Four States of Polish

Road	Specimen	No Polishing Effort	Low Polishing (10 cycles)	Medium Polishing (30 cycles)	High Polishing (80 cycles)
		BPN	BPN	BPN	BPN
RR	Core 1-1-1	57.2	70.5	65.6	59.7
	Core 1-1-2	52.5	72.1	65.2	52.2
	Core 1-1-3	52.9	67.6	65.4	49.9
	Core 1-1-4	55.7	66.4	67.1	53.6
	Core 1-2-1	56.9	67.0	67.2	52.8
	Core 1-2-2	56.1	65.9	66.6	52.7
	Gyratory 1 - Bottom	54.6	61.2	62.3	56.5
	Gyratory 1 - Top	70.5	73.5	69.5	60.6
	Gyratory 2 - Bottom	53.9	60.5	60.5	56.3
	Gyratory 2 - Top	70.2	73.2	70.1	71.6
	Gyratory 3 - Bottom	52.4	62.6	58.7	56.8
	Gyratory 3 - Top	70.2	70.7	70.7	70.3
	Gyratory 4 - Bottom	62.6	70.2	70.5	66.9
	Gyratory 4 - Top	71.1	71.1	66.8	70.7
	Gyratory 5 - Bottom	57.6	65.1	62.9	61.5
	Gyratory 5 - Top	69.6	70.1	67.7	62.2
	Gyratory 6 - Bottom	57.2	63.9	60.2	60.0
	Gyratory 6 - Top	67.7	57.8	69.4	68.4
	Gyratory 7 - Bottom	64.1	70.8	64.8	61.3
	Gyratory 7 - Top	70.2	68.8	69.1	68.0
FR	Core 1	69.7	74.0	60.6	61.5
	Core 2	68.1	72.6	64.1	62.5
	Core 3	65.5	73.6	71.1	65.8

Quick review of Table 6.12 confirmed that for most of the specimens tested, maximum BPN was generally observed after 10 cycles of polish, after which reduced BPN was observed with increasing polishing effort (see Figure 6.4 for example). This slight polishing effort would have removed much of the asphalt coating on the aggregate particles at the surface, exposing the underlying microtexture.

In addition, the gyratory specimens appeared to produce greater BPN than their respective core specimens at all four levels of polish, while the gyratory top specimens produced greater BPN than the bottom surfaces. Detailed analysis of the data is provided in Chapter 7.0.

Figure 6.4: Example of Change in British Pendulum Number with Laboratory Polishing

6.4 Laboratory Image Acquisition

6.4.1 Low Temperature Investigation with Mark I Pavement Surface Imager

To evaluate the change in surface characteristics with reduced temperature, the core and gyratory specimens were imaged with the Mark I Unit (4 lights) at temperatures of -15, -6, 0, 10 and 20°C. The specimens were cooled to -15°C in a freezer, removed, immediately imaged, and then placed on a table at room temperature. The warming of the specimens was monitored using an infrared thermometer and additional images were taken as the specimen surfaces reached the target temperatures. An example set of images taken with the Mark I unit is shown in Figure 6.5, in this case a POW core specimen at -15°C. Appendix 2 lists the images taken for the low temperature investigation and an external hard drive at Carleton University contains the images.

Figure 6.5: Example of Four Images Taken with Mark I Pavement Surface Imager

6.4.2 Polishing Investigation with Mark II Pavement Surface Imager

Imaging of the core and gyratory specimens was conducted (at room temperature only) on all specimens for each state of polish using the Mark II Unit (10 lights). A list of images taken during the polishing investigation is provided in Appendix 3 while the images themselves are provided on the external hard drive at Carleton University. An example set of images taken with the Mark II unit is provided in Figure 6.6, in this case for the SMA mixture used on road H174. Remembering that all of the images in this figure are of the same surface in the same location, the significant effect that lighting conditions have upon images is readily apparent.

Figure 6.6: Example of Ten Images Taken with Mark II Pavement Surface Imager

6.5 Image Processing

6.5.1 Photometric Stereo Method (Mark I Unit)

To derive a DEM using the PSM technique, each of the four greyscale images taken with the Mark I Unit for a given specimen were imported into MatLab as array data (i.e. a matrix 3007 columns by 2000 rows) with each entry containing a grey value ranging from 0 to 255. As per the Kim and Burger [1991] technique, ratios of the brightness values of Images 2, 3 and 4 over Image 1 were then calculated and formed a system of 3 equations with 3 unknowns (the surface normal vector components p and q , as well as depth, D). A single nonlinear equation for D was then derived and, using a seed value of depth, the equation was solved at each pixel location, with the resulting depth value providing an estimate of the depth value for the neighbouring pixel.

Unfortunately, although the computer was able to complete the analysis within an acceptable timeframe (a few minutes for each image set) the analysis technique was simply unable to resolve the depth map for such a detailed set of images (6 million pixels) over such a discontinuous surface, with the only roots found being zero. It appeared that the imaging system as constructed provided too many errors (lighting, lens quality, etc.) for the derivation of depth values using the PSM technique at the selected resolution.

As one goal of this investigation was to (cost effectively) map pavement surfaces in the microtexture range, reduction in image resolution and/or use of more expensive imaging equipment were not considered options. After much consideration, it was concluded that the PSM technique as proposed by Kim and Burger [1991] was currently unsuitable for this task and that modification to the imaging unit was required. Fortunately, after an extensive literature review it was discovered that Polynomial Texture Mapping (PTM) could be performed by modifying the Mark I unit through the addition of more point light sources.

6.5.2 Polynomial Texture Mapping (Mark II Unit)

PTM's for each image set (10 images) were developed using the PTM Fitter software freely available through Hewlett Packard at <http://www.hpl.hp.com/research/ptm/>. A light position (LP) file tells the software how many images are to be analyzed, as well as the location of each point light source with respect to the centre of the surface. As introduced in Section 3.6.6, the software then analyzes the change in brightness of each pixel within each of the 10 images and interpolates a polynomial function to represent the pixel brightness at any given lighting direction. The generated PTM file is then viewed using the PTM Viewer software. A screen shot of the PTM Viewer software with one of the H174 specimen PTMs is provided in Figure 6.7. Moving the mouse anywhere within the black circle (upper right hand corner of the screen) controls the lighting direction and the surface image is adjusted accordingly.

Figure 6.7: Screen Shot of PTM Viewer Software with H174 Specimen PTM

The PTM Viewer software is also able to output the surface normal vectors of each pixel. The resulting “image” assigns the x , y and z components of the surface normals to the red, green and blue colour channels, respectively. The channels are then separated into three individual grayscale images with brightness values ranging from 0 (black) to 255 (white). The grayscale values are then normalized with 0, 128 and 255 representing normal vector components of -1, 0, and +1, respectively. The three vector component images for a H174 specimen are shown in Figure 6.8.

With the surface normal vectors (p, q) available at each pixel location, it was hoped that an elevation model could be derived by integrating across the x - y plane as per the fundamental PSM relationships in Equation 6.1.

$$p = \frac{\partial \text{Depth}}{\partial x}; q = \frac{\partial \text{Depth}}{\partial y} \quad [6.1]$$

A sample set of surface normal vector images was sent to Dr. Jeffery Ho with the University of Florida, who has developed a method for integrating surface normal vectors using the Fast Marching Method [Ho et al. 2006]. Unfortunately, the Fast Marching Method did not appear suitable for the task. Dr. Ho provided the following discussion through email correspondence:

“Unfortunately, it seems that the problem is simply too difficult to be handled [with the Fast Marching Method]. The main technical issue here is to estimate a surface that is almost stochastic in the sense that its depth values seem almost random. Except perhaps for small patches where one can discern some continuity in the depth values. As the normal vector field is the only input we have, the discontinuities do not allow us to integrate the normal vector field directly to yield the depth. My current belief is that this will require a very different kind of algorithm.”

6.5.3 Discussion with Respect to Elevation Modelling of Asphalt Surfaces

The current investigation was not able to develop digital elevation models of the asphalt surfaces as proposed using the technique of Kim and Burger [1991], or through integration using the Fast Marching Method of Ho et al. [2006]. Notwithstanding, numerous advances and important relationships have been developed, as will be presented in Chapter 7.

As introduced in Section 3.8, successful integration of surface normal vector maps has recently been completed by others [El-Gendy and Shalaby 2007]. As such, a natural recommendation for future research would be to collaborate with those researchers using the extensive database developed during this investigation.

Finally, it is interesting to recognize that with the use of 10 lighting positions for PTM analysis, images taken during this investigation could be analyzed using the PSM techniques with multiple combinations of 4 lights. In other words, values of depth could be solved at each pixel location using different combinations of 4 of the 10 available lights. This analysis may be more robust because of the added redundancy. This is a numerical analysis problem and therefore beyond the scope of the current investigation.

a) X Vector Image

b) Y Vector Image

c) Z Vector Image

Figure 6.8: Example Surface Normal Vector Component Images for H174

6.6 Summary of Field, Laboratory and Image Database

It is important to review the magnitude of the database generated during this investigation, both to provide a sense of the considerable amount of effort that went into the research, as well as indicate the amount of data available for future analysis. In total, the laboratory and field testing programs generated 2100 data points (Tables 6.1 through 6.12, and Appendices), while the imaging and image processing effort resulted in 7068 images and/or image maps as follows:

Field Macrotexture data (MPD) = 9 road sections * 2 collection dates = 18 data points

Field Friction data (Mu) = 9 road sections * 2 collection dates = 18 data points

Field Friction data (normalized to 60 km/h) = 18 data points

Laboratory Mix Properties = 93 specimens * 17 mix properties = 1581 data points

Sand Patch testing (MTD) = 93 specimens * 1 test each = 93 data points

British Pendulum testing (BPN) = 93 specimens * 4 polish levels = 372 data points

Low Temperature images = 93 specimens * 4 images * 5 temperatures = 1860 images

Input Images for PTM = 93 specimens * 10 images * 4 polish levels = 3720 images

Polynomial Texture Maps = 93 specimens * 4 polish levels = 372 maps

Surface Normal Vector maps = 372 PTM's * 3 vector maps each = 1116 maps

A summary of the data points and analyses generated during the data analysis effort (not included in the above) is provided in Section 7.10. Finally, it is interesting to note that to follow the requirements of ASTM E303, a minimum of 1860 swings of the British Pendulum arm were completed during this investigation.

CHAPTER 7: DATA ANALYSIS AND RESULTS

7.1 Chapter Objective

The sampling and imaging schedule presented has been developed to investigate the following relationships:

- i) The difference in textural and frictional properties provided by field vs. gyratory compaction. Differences between the top and bottom surfaces of the gyratory specimens are also discussed.
- ii) The difference in textural and frictional properties between individual mix types and their constituent materials.
- iii) The change in frictional properties with polishing.

As outlined previously, the primary objective of this investigation is to determine whether digital image analysis measures can be used to objectively quantify pavement frictional properties under the changing conditions listed above.

7.2 Texture Results

7.2.1 MTD of Gyratory Surfaces – Top vs. Bottom

The Mean Texture Depth (MTD) values from sand patch testing on the top gyratory surfaces were first plotted against the MTD from the bottom surfaces as shown in Figure 7.1. The top surface MTD is 42% greater than the bottom surface MTD (the intercept was not statistically significant). Excellent correlation was observed with a linear relationship ($R^2=0.93$) according to Equation 7.1.

$$MTD_{TopSurface} = 1.42 * MTD_{BottomSurface} \quad [7.1]$$

Figure 7.1: MTD Results for Top and Bottom Gyratory Surfaces

Further inspection of Figure 7.1 suggested that the higher texture values for H174 (the open-graded SMA) might be dominating the relationship. When only the dense-graded mixes were included, a more modest correlation was observed ($R^2=0.59$) although the resulting linear relationship (Equation 7.2) is very similar with the MTD from the top surface 40% greater than the MTD from the bottom surface.

$$MTD_{TopSurface} = 1.40 * MTD_{BottomSurface} \quad [7.2]$$

The difference in MTD between the gyratory surfaces could be attributed to segregation of the mix as it was poured into the mould or the different boundary conditions imposed by the completely confined mould bottom and the top surface. A combination of both factors may also

be involved. Specific determination of the cause of the increased texture observed on the gyratory top surface was not an objective of this investigation, however, it is anticipated that this difference would be observed with all gyratory compactors (i.e. regardless of manufacturer) as the moulds, ram pressure and compaction angle are the same.

7.2.2 MTD of Gyratory Specimens versus Core Specimens

It was important to determine the potential use of the gyratory MTD values to predict field MTD values as obtained with the core specimens. In this document, the use of the terms “field” and “core” are synonymous when discussing MTD.

A series of linear and polynomial relationships were examined (Table A.1 in Appendix A). When all mixes were included, a second order polynomial relationship between the gyratory top surfaces provided the best fit with the respective field compacted surfaces (Figure 7.2).

However, as there is a considerable gap in the MTD values between 0.6 and 1.4 mm (field MTD values), the dense-graded dataset might actually be best represented with a linear relationship (also shown in Figure 7.2). This data gap is the result of a single nominal aggregate size in all of the mixes (12.5 mm) - the most commonly used size for Ontario roadways. Values of MTD within the existing gap could be achieved by testing dense-graded surface mixes prepared with larger aggregates (such as HL4 that incorporates a 16 mm nominal size) or gap-graded surface mixes prepared with smaller aggregates (such as a 9.5 mm SMA). Evaluation of dense-graded mixes incorporating aggregates smaller than 12.5 mm (nominal) should also be completed to confirm whether the relationships are valid below MTD values of 0.3 mm.

However, until additional texture data is available, Equations 7.3 and 7.4 may be used with engineering judgement to estimate the field MTD values from gyratory sand patch testing:

$$MTD_{Field} = 1.14(MTD_{Top})^2 - 0.81(MTD_{Top}) + 0.40 \quad [7.3]$$

$$MTD_{Field} = 0.52(MTD_{Top}) + 0.05 \quad [7.4]$$

Where: MTD_{Field} is the estimated field MTD (mm) from sand patch testing and MTD_{Top} is the MTD (mm) of the top surface of the gyratory specimen.

Figure 7.2. Best-Fit Relationships Between Gyratory MTD and Field MTD

7.2.3 MTD of Gyratory and Core Specimens versus As-Constructed Field MPD

Sand patch testing in the field requires considerable effort, expense and operator risk due to the requirement for traffic control. At the present time, high speed macrotexture testing may only be accomplished using laser sensors. The Mean Profile Depth (MPD) parameter (as per ASTM E1845) provides a measure of the macrotexture depth along a single line (profile) as opposed to the sand patch test, which measures the average texture depth over an area. As a result, there are differences in the value of MPD and MTD for the same pavement surface. ASTM provides a conversion formula, which will be discussed in the following section.

The MTD values obtained from the gyratory top surfaces, as well as the core specimens were plotted against their respective average MPD values from field testing with the OPQ laser (Figure 7.3).

When all mixes were included, the gyratory MTD values displayed a polynomial relationship with the field MPD values, whereas a weak linear relationship was observed when only the dense-graded mixes were included. Given the considerable data gap, as well as the scatter of the gyratory top surface data, it does not appear that the gyratory top specimen can be used to predict field MPD at this time.

In contrast, a strong linear relationship was observed between the field MTD values and the MPD values. Indeed, the same linear relationship was observed whether including all of the core data ($R^2=0.99$), or just the dense-graded mixes ($R^2=0.81$), with MPD values 86% greater than their respective MTD values. As such, estimating field MPD values from MTD values collected from core specimens (Equation 7.5) appears valid regardless of the existing data gap, although additional testing is suggested to confirm.

$$MPD = 1.86(MTD_{Core}) \quad [7.5]$$

7.2.4 Field MPD and Estimated MTD based on ASTM E1845

ASTM E1845 provides a linear relationship to estimate MTD from MPD as provided in Equation 7.6.

$$MTD = 0.008 + 0.8 * MPD \quad [7.6]$$

Rearranging Equation 7.6 for MPD suggests that MPD values should be approximately 25% greater than MTD values plus an additional intercept value that translates into an additional 0.8 to 1.6% between MPD values between 1.0 and 0.5 mm, respectively. However, the MPD results measured during the current investigation (Section 7.2.3) are considerably higher than those suggested by the ASTM formula (86% versus approximately 25%).

Figure 7.3. Mean Profile Depth versus Mean Texture Depth

The intent of this investigation was not to confirm or dispute the ASTM formula, however, the results suggest that caution be taken when converting between MPD and MTD (and vice versa).

7.2.5 Change in Field MPD with Time

The change in as-constructed MPD and MPD after one year in service is shown graphically in Figure 7.4. Significant change in MPD with time would only be expected if a) significant loss of surface material (ravelling) had occurred leading to an increase in MPD, b) bleeding of the asphalt cement, or c) contamination of the surface with debris had occurred leading to a decrease in MPD.

In general, only a small change in MPD was observed, which can be attributed to the relatively high coefficient of variation (COV) in the data (ranging from 6.7 to 24%). The relatively large increase in MPD observed for POW may be the result of ravelling, as this mix had relatively low initial asphalt cement content and film thickness. Using the Asphalt Institute MS-2 method [1997], a weak relationship between reduced initial film thickness and increase in MPD from initial construction to 1-year in service was observed, however the coefficient of determination (R^2) was only 0.20 so no further effort was made in this regard.

Figure 7.4: As-Constructed and 1-Year Mean Profile Depth

7.3 Laboratory Friction Results

7.3.1 Initial British Pendulum Number of Core Specimens

The average BPN of the unpolished core specimens for each road is presented in Figure 7.5 organized by the type of aggregate used in the mix. At first glance, the results did not appear to make sense; the mixes incorporating only limestone (SLR, OCR, UDHS and UDH3) provided slightly greater BPN than the mixes whose coarse aggregates consisted of dolomitic sandstone (RR and POW). Most surprisingly, the SMA mixture with 100% dolomitic sandstone (H174) had the lowest initial BPN of all mixtures tested. As will be detailed later, the type of aggregate is only one factor contributing toward initial friction – with asphalt film thickness playing an important role.

Figure 7.5: Unpolished British Pendulum Number of Laboratory Specimens

The two mixes (FD and DR) incorporating a combination of limestone and traprock yielded the greatest initial BPN. The traprock was introduced to the mix through the addition of 3% of manufactured shingle modifier (MSM) – essentially the scraps resulting from the shingle production process that were ground up into a finely graded product. As asphalt shingles contain asphalt cement, hard and durable traprock, as well as cellulose fibres, they are readily added to asphalt concrete. To the author’s knowledge, this is the first study to document a substantial gain in BPN as a result of the addition of MSM – particularly in such a small quantity.

7.3.2 Initial British Pendulum Number of Gyratory Bottom Specimens

The average BPN of the unpolished gyratory bottom specimens for each road is also presented in Figure 7.5. With the exception of DR, the bottom surfaces produced greater BPN than the core surfaces on average, although as will be presented in Section 7.3.5 there were numerous individual gyratory bottom BPN values the same or lower than the respective core surfaces.

Like the core specimens, the H174 gyratory bottom surfaces displayed a thick initial asphalt film. However, the average BPN of the H174 gyratory bottom surfaces was considerably greater than the average core BPN. As such, another mechanism(s) must have been responsible for the large increase in BPN as compared to the cores. With reference to Table 6.11, the average MTD for the H174 gyratory bottom surface was considerably less than the core surface, thereby presenting additional contact area to the British Pendulum shoe.

7.3.3 Initial British Pendulum Number of Gyratory Top Specimens

The average BPN of the unpolished gyratory top specimens for each road is presented in Figure 7.5 as well. Unlike the cores and gyratory bottom specimens, the intuitive relationships between aggregate type and BPN were generally observed with the gyratory top specimens; the mixes incorporating sandstone coarse aggregate (RR and POW) yielded slightly greater initial

BPN than those incorporating limestone alone (SLR, UDHS and UDH3). Upon further inspection of the gyratory top surfaces, however, it was apparent that some aggregate fracture was imposed by the gyratory compactor (Figure 7.6), thus exposing additional microtexture.

Figure 7.6: Aggregate Fracture Observed with Gyratory Top Surfaces

The introduction of the MSM traprock into mixes FD and DR increased the BPN to the same level as those incorporating sandstone coarse aggregate. Given the small percentage of MSM added (3% by mass) as compared to the large percent of premium sandstone incorporated into mixes RR and POW (50%), the use of MSM could represent a very cost effective way to increase initial friction of mixes.

7.3.4 Change in British Pendulum Number with Polishing

The BPN values for each road section (core specimens) were averaged at each level of polish and are shown in Figure 7.7. Most mixes exhibited a similar curve; an increase in BPN from the as-constructed (unpolished) state to the low level of polish (10 cycles), followed by a reduction in BPN at 30 cycles and a further reduction at 80 cycles. Interestingly, two mixes (H174 and UDHS) did not display further loss in BPN between 30 and 80 cycles of polish, suggesting a refreshing of the microtexture with polishing action. This result is completely reasonable for H174 (an SMA mix with 100% sandstone), however one would not anticipate this result for the limestone UDHS mixture as this aggregate type is prone to polishing. The POW mixture did not obtain maximum BPN until 30 cycles of polish were imposed.

Figure 7.7: Average Change in British Pendulum Number with Polishing (Cores)

On average, the core specimens containing limestone exhibited a 15% increase in BPN with 10 cycles of polish. Similarly, the core specimens containing sandstone coarse aggregate or limestone with traprock exhibited an average increase of 11.8% BPN (13.6% if the total increase in BPN for POW is used), while the SMA mixture with 100% sandstone exhibited an average increase of 22.4% in BPN. The microsurfacing specimens displayed an average of 8.3% increase in BPN.

The gyratory bottom specimens containing limestone exhibited a 4.3% increase in BPN with 10 cycles of polish while specimens containing sandstone coarse aggregate or limestone with traprock exhibited an average increase of 7.1% BPN (8.7% if the total increase in BPN for POW is used). The SMA mix exhibited an average increase of only 0.2% BPN with 10 polish cycles, although the initial friction was considerably higher than the respective core specimens.

The response of the gyratory top specimens was inconsistent. Those whose mixes contained limestone exhibited an overall 2.0% increase in BPN with 10 cycles of polish, however the OCR specimen displayed reduced friction with 10 polishing cycles. The specimens containing sandstone coarse aggregate or limestone with traprock exhibited an average reduction of 1.1% BPN (but an increase of 0.4% if the total increase in BPN for POW is used). The SMA mix exhibited an average increase of 7.0% BPN with 10 polish cycles although the initial friction was considerably higher than the respective core specimens.

The next step was to determine whether the laboratory compacted surfaces could be used as a surrogate for the field compacted surfaces with respect to British Pendulum testing.

7.3.5 Statistical Comparison of Core and Gyratory Specimen Surfaces

Comparison of the macrotexture depth (MTD) data completed in Section 7.2.2 suggested that the gyratory top surface best predicted the as-constructed surface. To compare the surfaces with respect to BPN, two sets of statistical tests were completed. First, a series of Tukey and

Dunnett tests were completed to determine whether or not there were any significant differences in BPN between specimen type at each level of polish. The Tukey Honestly Significant Difference (HSD) test is a multiple comparison test (i.e. all pairs are of interest) while the Dunnett test sets a reference mean (in this case the core specimens) and compares other datasets to that reference. The detailed results are provided as Table A.2 in Appendix A.

Next, a series of 1-way ANOVA f-tests were then completed to evaluate the change in friction from one level of polish to another by specimen type. The one-way f-tests are more appropriate when evaluating changes to the same specimens as opposed to pairwise comparisons between different specimens. The detailed results are provided in Table A.3 in Appendix A for reference.

With the exceptions of H174 and UDHS, both the Tukey HSD and Dunnett two-sided comparison tests indicated that no significant differences between the BPN values measured on the core and gyratory bottoms specimens were observed at any level of polish, including the as-constructed state while the gyratory top surface was significantly different to the core and/or bottom surface in most cases.

For H174, there were no significant differences between the top and bottom gyratory surfaces, but there were significant differences between the gyratory surface and the core surfaces. As such, it appears that gyratory specimens of SMA cannot be used to accurately predict the respective field constructed BPN.

For UDHS, the comparison tests seemed to suggest that the gyratory top surfaces provided the same BPN values as the core specimens, however, when the BPN data from all densely-graded mixes were combined by specimen type into a single dataset, there were no significant differences between the core and gyratory bottoms specimens.

As such, it appears that the gyratory bottom specimen can be used as a surrogate for the field compacted surface for British Pendulum testing (no SMA), whereas the gyratory top specimen is not statistically suitable for this purpose, particularly when no polishing effort has been applied.

Similar observations were observed in Table A.3 (Appendix A). First, when all roads were combined into a single dataset (including the SMA), the change in BPN from one state of polish to another (ie. the unpolished state to the low polish state, the low polish state to the medium polish state, etc.) was statistically significant for the core specimens. Specifically, the f-statistic was greater than the critical value for the respective number of samples, indicating that the null hypothesis (that the two datasets were statistically the same) could be rejected. The only exception occurred when comparing the unpolished state to the high polish state (80 cycles), where no statistically significant difference was observed. This result is interesting because it suggests that long term friction is the same as the unpolished state, which was observed by Emery et al. [1982].

Reviewing the ANOVA tests by road for the core specimens, additional exceptions were noted. For POW, the change in friction from unpolished to low polish was not statistically significant, which was not surprising since POW did not achieve peak friction until the medium level of polish (30 cycles) at which point statistical significance was observed. For DR, UDHS and UDH3, the core specimens displayed a statistically significant difference at 80 polish cycles as compared to the unpolished state. For DR, the BPN values at 80 polish cycles were lower than the unpolished state, whereas greater values were observed after high polish for UDHS and UDH3. The change in friction between 30 and 80 cycles was not significant for many roads, suggesting that friction had reached a plateau.

Of particular interest to this investigation was that statistical significance between polish levels observed with the gyratory bottom specimens mirrored that observed with the core specimens, while the gyratory top specimens did not. As such, the bottom gyratory surfaces appear to best emulate the behaviour of the field cores, while the top surfaces do not appear to follow a rational pattern when subjected to polishing effort. The only exception was H174.

7.3.6 Estimating Field British Pendulum Number from Gyratory Bottom Specimen

The statistical comparisons completed in Section 7.3.5 indicated that with the gyratory bottom surfaces best matched the field compacted surfaces for the dense-graded mixtures. A comparison of the average BPN for the core specimens and the average BPN for the respective gyratory bottom surfaces for all levels of polish is presented by road section in Figure 7.8. Four points are presented for each road with each point representing the average BPN for a particular road at a specific state of polish. As shown, the dense-graded mixes followed a 1-to-1 relationship of BPN between the average core and gyratory bottom surfaces.

The coefficient of determination (R^2) is not very high at 0.39, however, with additional data the strength of the relationship is expected to improve.

Figure 7.8: Comparison of British Pendulum Number of Cores versus Gyratory Bottoms (SMA specimens removed)

7.4 Field Friction Results

7.4.1 Change in Field Friction from Initial Measurement to 1 Year in Service

The speed corrected mu values are plotted in Figure 7.9. As shown, all of the limestone mixes displayed a reduction (average 8.6%) in mu value after only 1 year in service. Conflicting results were observed with the limestone mixes incorporating some traprock (DR and FD), while POW observed a 6.4% increase in friction. The microsurfacing (FR) observed a 7.3% reduction in mu value while the SMA mixture (H174) observed a 5.4% reduction in friction. Additional analysis by aggregate type is provided in the following sections.

Figure 7.9: Change in Speed Corrected Coefficient of Friction after 1 Year in Service

7.4.2 Change in Field Friction for Mixes with Limestone Aggregates

An interesting pattern of change in coefficient of friction was observed when reviewing Table 6.6 for Roads SLR, UDH3 and OCR, which incorporate the same aggregate type (limestone) and PG asphalt cement. First of all, after 1 year of trafficking, all three road sections revealed similar mu values (0.78, 0.76 and 0.79, respectively). Also interesting was that the initial mu values for these roads appeared to decrease with age after construction – i.e. at 2 days the mu value for SLR was 0.88, at 9 days the mu value for UDH3 was 0.84 and at 17 days the mu value for OCR was 0.76.

To obtain an initial sense of how friction might change with trafficking, the mu values for the HL3 mixes with limestone (SLR, OCR and UDH3) were plotted against cumulative number

of vehicles at time of testing (using the data from Table 6.2), as shown in Figure 7.10. Well-behaved logarithmic and power relationships (similar in shape to those observed with the laboratory polishing effort) were observed between the total number of vehicles and speed-corrected mu values. Weaker correlation was observed with number of ESAL's (not shown), which made sense given that ESAL's include only heavy vehicle traffic (i.e. trucks).

Figure 7.10: Change in Mu with Trafficking for HL3 Mixes with Limestone Aggregate

Recognizing that this dataset is very limited, the results tend to suggest that maximum friction for these mixes was observed sometime between initial construction (0 vehicles) and 2 days of trafficking (approximately 1500 vehicles), although unfortunately as no testing was completed within 2 days the actual maximum value is not known with certainty. After 2 days of

trafficking, the reduction in μ value became much more gradual and levels off (i.e. remains relatively constant) with trafficking above 200,000 vehicles.

As the actual maximum value of coefficient of friction could not be determined, comparison between the polishing affect from the number of vehicles travelling over the pavement surface and that imposed with the sandpaper polishing in the laboratory could not be conducted with certainty. However, the fact that the shape of the curves shown in Figure 7.10 and Figure 6.4 are similar suggests that the laboratory polishing effort mimics that observed in the field under traffic.

Insufficient data was available to evaluate the change in friction with trafficking for the mixes with other aggregate combinations.

7.5 International Friction Index

7.5.1 IFI Field versus IFI Laboratory

The average “Golden” friction value at 60 km/h (F_{60}) for each test section based on the field measurements shortly after construction (Table 6.6) were compared to those calculated for the core, gyratory bottom and gyratory top specimens in the unpolished state using the constants for BPN and MTD in Table 6.5 and plotted in Figure 7.11.

One would hope to see a one-to-one relationship, however the field IFI constants were not calibrated to the T10 trailer and OPQ laser. As such, the laboratory based IFI values of F_{60} and Sp should be considered more accurate than the field values.

Figure 7.11. Average Golden Friction Number at 60 km/h (F60) from Field Measurements and Laboratory Measurements

7.5.2 Predicting Core IFI from Gyratory Specimens

Recognizing that the IFI values of $F60$ and Sp calculated based on BPN and MTD values from the core specimens better represent the field conditions than the IFI values from actual field measurements with the T10 trailer and OPQ laser (at least until the appropriate calibrations can be completed), the next objective was to determine whether the gyratory specimens could be used to predict the IFI values of the cores.

Section 7.2.2 indicated that sand patch testing of the gyratory top specimen produced more accurate estimation of the core MTD, whereas Section 7.3.5 indicated that British Pendulum testing of the gyratory bottom specimen produced more accurate estimation of the core BPN. As such, the best results for predicting field IFI should be achieved by calculating Sp from

MTD values from the gyratory top specimens and $F60$ from BPN values from the gyratory bottom specimens.

Figure 7.12 displays the relationship of the $F60$ calculated from the gyratory specimens (MTD from gyratory tops and BPN from gyratory bottoms) to those of the core specimens (which are field compacted specimens). As shown, the gyratory specimens can be used to predict field IFI values (as represented by the core specimens) according to Equation 7.8 ($R^2 = 0.84$).

$$F60_{Core} = 0.80 * F60_{Gyratory} - 0.04 \quad [7.8]$$

The primary reason why a 1-to-1 relationship between $F60_{Core}$ and $F60_{Gyratory}$ was not observed was due to the differences in macrotexture (MTD) between the core and gyratory top surface.

Figure 7.12: F60 from Core Specimens versus F60 from Gyratory Specimens

7.6 Estimating Macrotexture Depth from Mix Properties

7.6.1 Mean Texture Depth from Mix Properties

To provide one or more predictive models for estimating field texture based on mix properties, a correlation matrix was first developed from the Table 6.7 data. The highest single parameter correlation observed was between the coefficient of curvature (C_c) and MTD with a correlation (r) value of 0.97. High positive correlation was also observed between the fineness modulus, FM ($r = 0.83$) and voids in the mineral aggregate, VMA ($r = 0.59$). High negative correlation was observed for the mass percent of aggregate passing the 4.75mm sieve, $P4.75$ ($r = -0.93$) and the bulk relative density of the compacted core, BRD ($r = -0.58$).

As series of data fitting efforts were then completed, as described in the following sections.

Fineness Modulus, Percent Passing 4.75 mm Sieve, VMA and BRD

As the FM and $P4.75$ values were not independent of one another ($r = -0.93$), they could not be used together in a regression analysis without some sort of initial transformation. The VMA and BRD values were also not independent of one another ($r = -0.87$) and would also require transformation prior to inclusion in a single regression model.

A plot of FM versus MTD yielded a second order polynomial relationship similar to that observed by Prowell and Hanson [2005] when developing Equation 2.19. However, the relationship was not stable for low values of FM (below 4.3) where it began to yield increased MTD values. To stabilize the relationship and bring in additional mix information, the MTD was plotted against the product of FM and VMA with the resulting relationship remaining a second order polynomial. The product of $P4.75$ and BRD was also calculated to investigate the

behaviour of the negatively correlated mix properties. A negative polynomial relationship was observed.

As opposite polynomial relationships with MTD were observed, a third relationship was attempted by dividing the product of *FM* and *VMA* by the product of *P4.75* and *BRD*. The resulting linear model shown in Figure 7.13 and as Equation 7.9 allows the inclusion of four of the most highly correlated independent variables while addressing their statistical co-dependency. The standard error for Equation 7.9 was 0.114 mm and the intercept was significant at the 95% confidence level.

$$MTD_{Field} = -0.24 + 0.981 \left(\frac{FM * VMA}{P4.75 * BRD} \right) \quad [7.9]$$

Equation 7.9 suggests that increased macrotexture may be achieved through the use of gap-graded aggregates (increased fineness modulus), provision of more void space between aggregate particles (increased *VMA*), use of coarser mixes (increased aggregate retention on the 4.75 mm sieve) or by using less compactive effort (i.e. reduced density). Each of these four alternatives makes intuitive sense and Equation 7.9 can account for changes in these properties both individually or in concert.

Clearly, a considerable gap in MTD values exists between the densely-graded mixes and the open-graded SMA. All mixes tested were 12.5 mm nominal maximum aggregate size. As a result, a definitive “model” cannot be currently stated with these parameters. Future investigations should involve texture testing of other surface mixes such as HL4 (16.0 mm nominal maximum aggregate size) and 9.5 mm SMA, which should provide MTD values within the missing range of 0.6 and 1.4 mm.

Figure 7.13. Estimating MTD from Mix Properties (Equation 7.9)

Coefficient of Curvature and Dust to Binder Ratio

As was initially reported in Goodman et al [2005], the coefficient of curvature (C_c) did not respond well to the addition of other variables and was therefore considered no more beneficial than the model developed by Prowell and Hanson [2005] using solely the fineness modulus.

Since that time, however, additional analysis of the C_c parameter suggested another relationship for estimating macrotexture. The Dust to Binder ratio (DBR) was positively correlated to MTD ($R=0.69$), as well as the C_c parameter (0.69). When the C_c was divided by DBR (or multiplied by the inverse of the DBR), the resulting parameter provided enhanced predictive capability for estimating MTD as shown in Figure 7.14 and Equation 7.10.

$$MTD_{Field} = 0.07 \left(\frac{C_c}{DBR} \right) + 0.25 \quad [7.10]$$

Alternatively, Equation 7.10 can be rewritten as Equation 7.11.

$$MTD_{Field} = 0.07 \left(\frac{C_c * \%AC}{\%Dust} \right) + 0.25 \quad [7.11]$$

Where $\%AC$ is the mass percentage of asphalt cement by mass of aggregate and $\%Dust$ is the mass percentage of the gradation passing the 0.075 mm sieve.

Unfortunately, while suggesting an overall trend with increasing MTD, the use of C_c and DBR to estimate MTD (Figure 7.14) tends to cluster the mixes by gradation type. As shown, the fine, densely-graded mixes (SLR, OCR, DR, UDH3, UDHD, FD) are similarly grouped, as are the coarse, densely-graded mixes (POW and RR) and coarse, open-graded mix (H174) respectively. As such, while a general sense of macrotexture depth may be obtained, accurate estimation of MTD based on Equation 7.11 is not anticipated.

Figure 7.14: Estimating MTD from Mix Properties (Equation 7.11)

Predicting MTD using NCAT 2000 Model based on Fineness Modulus

Fineness modulus values from the current investigation were entered into the model to predict MTD developed by Prowell and Hanson [2005]. Figure 7.15 plots the resulting values against actual MTD values measured during this investigation with the sand patch test. As shown, the model does not provide a 1-to-1 estimation of MTD and, as observed with Equation 7.11, there appears to be clustering of the data according to mix type. As such, accurate estimation of MTD based solely on fineness modulus is not anticipated, although a general sense (order of magnitude) may be obtained.

Figure 7.15: MTD Predicted using NCAT 2000 Equation from Prowell and Hanson [2005]

7.6.2 Mean Profile Depth from Mix Properties

Coefficient of Curvature and Dust to Binder Ratio

Equation 7.11 was calibrated to predict MPD as well, which is presented as Equation 7.12 ($R^2=0.98$) and shown graphically in Figure 7.16.

$$MPD_{Field} = 0.14 \left(\frac{Cc * \%AC}{\%Dust} \right) + 0.46 \quad [7.12]$$

Again, the fine, densely-graded mixes (SLR, OCR, DR, UDH3, UDHD, FD) are similarly grouped, as is the coarse, densely-graded mix (POW) and the coarse, open-graded mix (H174) respectively. The small number of data points available makes the use of Equation 7.12 appropriate only for obtaining a relative estimation of MPD only.

Figure 7.16: Estimating MPD from Mix Properties (Equation 7.12)

7.7 Estimating Initial Friction from Mix Properties

Fineness Modulus, Percent Passing 4.75 mm Sieve, AC Content and BRD

As with the macrotexture data, a series of data fitting exercises were conducted to investigate one or more relationships between mix constituent and volumetric properties with their respective field specimen BPN values (from the core specimens). Interestingly, good correlation to initial field BPN was observed with the same variables used in Equation 7.9 for the macrotexture investigation (*FM*, *VMA*, *P4.75* and *BRD*), however, their respective effects were inverted. Specifically, increased BPN was observed through the use of more densely graded aggregates (reduced *FM*), less void space between aggregate particles (less *VMA*), use of finer gradation (more passing the 4.75mm sieve) and higher compactive effort (increased *BRD*).

However, while the *VMA* parameter includes the volumetric percentage of asphalt cement contained in the mix (as well as the volume of air), it was observed that the mass percentage of asphalt cement – commonly referred to as asphalt cement content – was better correlated with BPN. This result made intuitive sense particularly upon review of the SMA specimens, as a thick asphalt cement coating on the coarse aggregate particles reduced the initial BPN values considerably without affecting the macrotexture. Indeed, poor early life skid resistance of SMA and other binder-rich mixes has been documented [Halligan 2006].

Asphalt cement content was therefore incorporated into a new relationship between mix properties and initial field BPN according to Equation 7.13 ($R^2=0.69$).

$$BPN_{InitialField} = 42.32 + 2.95 \left(\frac{P4.75 * BRD}{FM * AC} \right) \quad [7.13]$$

A logarithmic trendline using the Equation 7.13 parameters provides the same predictive accuracy ($R^2=0.69$) and is provided as Equation 7.14 and shown in Figure 7.17.

$$BPN_{InitialField} = 39.2 + 11.78 \ln \left(\frac{P_{4.75} * BRD}{FM * AC} \right) \quad [7.14]$$

Interestingly, the data in Figure 7.17 is less clustered than that observed with the macrotexture data, although data gaps remain.

Values of the independent variable in Equation 7.14 within the range of 2 to 4.5 are required to confirm the relationship. Such values may be obtained with more aggregate material retained on the 4.75mm sieve, reduced density, a gap-graded aggregate structure (i.e. higher fineness modulus), increased asphalt cement content, or a combination of all of these variables. A 9.5mm SMA mixture would likely provide values within the missing range.

Figure 7.17. Prediction of British Pendulum Number (Cores) with Equation 7.14

Coefficient of Curvature and Dust to Binder Ratio

The invert of the Equation 7.11 parameters (Dust to Binder Ratio and Coefficient of Curvature) was also used to predict initial BPN as provided in Equation 7.15 ($R^2=0.66$) and Figure 7.18. As shown, a logarithmic relationship was apparent.

$$BPN_{InitialField} = 59.2 + 3.6LN\left(\frac{DBR}{Cc}\right) \quad [7.15]$$

As shown, there are no considerable data gaps with the use of *DBR* and *Cc* such that Equation 7.15 may be considered a reasonable model for estimating initial field BPN from mix properties, although additional data would further enhance the predictive capability.

Figure 7.18: Prediction of British Pendulum Number from Equation 7.15

Asphalt Film Thickness, Percent Passing the 2.36mm Sieve, Fineness Modulus and BRD

As a final effort, the affect of asphalt film thickness on initial BPN was investigated. While AC content (by mass of aggregate) yielded a correlation coefficient R of -0.61 when related to initial BPN, the film thickness values calculated using the Index and Virtual Methods provided increased correlation at -0.83 and -0.84, respectively.

Further review of the gradation correlation coefficients indicated that the percent passing the 2.36mm sieve was better correlated to initial BPN than the 4.75mm sieve. This is an interesting finding as the 2.36mm sieve is referred to as the Primary Control Sieve for Superpave 12.5mm mixes. The PCS determines whether the mixture is considered fine or coarse.

Two additional equations were developed this time using a composite parameter involving the product of the fineness modulus, FM and the asphalt film thickness, FT (Index or Virtual methods) subtracted from the product of the percent passing the 2.36mm sieve, $P_{2.36}$ and the bulk relative density, BRD as provided in Equations 7.16 ($R^2=0.73$) and 7.17 ($R^2=0.77$). These models are shown in Figure 7.19.

$$BPN_{InitialField} = 54.8 + 0.14(P_{2.36} * BRD - FM * FT_{Virtual}) \quad [7.16]$$

$$BPN_{InitialField} = 52.9 + 0.15(P_{2.36} * BRD - FM * FT_{Index}) \quad [7.17]$$

The resulting equations group the asphalt mixes by surface texture type, although to a much less extent than observed with the macrotexture data. Coarse, open-graded mixes produced negative values (notice that one of the POW specimens was slightly negative as well). The coarse, dense-graded mixes were slightly positive while the fine, dense-graded mixes were more largely positive. Interestingly, the fine, dense-graded mixes incorporating both limestone and traprock aggregates (through the addition of MSM) were grouped separately from the other fine, dense-graded mixes with limestone alone.

Figure 7.19: Estimating Initial BPN with Mix Properties

A Word About the Relationships

It must be noted that relationships developed during this research are provided for reference purposes and require significant additional data and development before use for estimating initial field BPN values from mix design parameters. Most notably absent are parameters concerning aggregate hardness, polish resistance or petrography, which were not available at the time of analysis. It may, however, be argued that the relative importance of aggregate composition toward initial friction is not as great as the contribution to long-term polish resistance – particularly in the City of Ottawa where all paving aggregates are produced from quarry sources. Continued evaluation of the gyratory and field specimens with increasing levels of polish will certainly require consideration of aggregate properties.

7.8 Estimating Macrotexture with Image Analysis

7.8.1 Overview

As already introduced, the provision of adequate macrotexture is important to ensure bulk water drainage and avoid hydroplaning – particularly as vehicle speed increases. The sand patch test although widely used and inexpensive in terms of equipment cost, requires considerable time to complete, is subject to operator bias and cannot be completed in windy conditions. In a recent but unrelated field data collection effort, the author required 60 minutes to complete 9 sand patch tests – an average of 6.7 minutes per test.

While the OPQ laser sensor collects macrotexture data at high speed, it is relatively expensive and only collects data along a single line (whereas macrotexture is an area-based feature). Furthermore, recent correspondence with Dr. John J. Henry of CDRM Inc. (and co-developer of the International Friction Index) indicated that “obtaining a reliable value of MPD is critical and that some of the vehicle mounted laser devices do not produce suitable MPD for use with the IFI, particularly at high speeds [Henry 2009].” Fortunately, the results of this research effort have provided the foundation for an image-based analysis technique to replace the sand patch test and laser based texture devices, as presented in the following sections.

7.8.2 Estimating MTD with Lacunarity Analysis of PTM Z-Vector

The z-component of the surface normal vector represents the change in pixel orientation with respect to the horizontal (x-y) plane – i.e. the change in elevation (as opposed to the actual elevation itself). As such, the z-component image provides a pseudo-elevation map because rapid changes in the z-vector should correspond to the presence of peaks or valleys in the surface. This is the case when comparing the z-vector image to the actual surface as shown in Figure 7.20. Both peak and valley areas in the surface (a) are highlighted in the z-vector image (b).

a) Pavement Surface – note peak area (oval) and deep valley (circle)

b) Z-Vector Image – peak area (oval) and deep valley (circle) are highlighted

Figure 7.20: Comparison of PTM Z Vector Image and Actual Pavement Surface

Table 7.4. Box Sizes for Lacunarity Analysis of PTM Z-Vector Images

Box Size (pixels)	Aggregate Size, mm (sieve size, mm)
1 to 30	0.03 to 0.898 (0.075, 0.150, 0.300, 0.600)
39	1.167 (1.16)
78	2.335 (2.36)
158	4.729 (4.75)
317	9.488 (9.5)
636	19.036 (19)
1279	38.281 (38)

Lacunarity analysis, as presented in Section 3.5, evaluates texture at multiple pattern scales and highlights dominant pattern sizes, as well as the rate of change in pattern size. By evaluating the z-component image of the surface normals, it was hoped that features in the resulting lacunarity curves would relate to the MTD as measured by the sand patch test.

As with the lacunarity of the Schonfeld images in Section 4.3.4, the z-vector images were analysed using Image J with the FracLac plugin. The images were first converted to binary using the histogram thresholding functionality and then lacunarity was calculated at various box sizes as presented in Table 7.4. Additional sizes were used as required to confirm observed trends.

Example graphs showing the slope of lacunarity versus particle size are shown in Figures 7.21 (all particle sizes), as well as Figure 7.22 (zoomed to show 0.03 to 5 mm particle sizes).

Figure 7.21: Example Lacunarity Slope Graphs of Z-Vector Images (All Particle Sizes)

Figure 7.22: Example Lacunarity Slope Graphs of Z-Vector Images (Sizes 0.03 to 5mm)

As shown, the plot of lacunarity slope for all mixes became asymptotic after texture sizes of approximately 10 mm, which was reasonable given that the nominal maximum particle size in the mixtures was 12.5 mm. It is important to recognize that lacunarity analysis investigates texture size, not necessarily particle size although occasionally this is one and the same.

Figure 7.22 clearly shows that lacunarity analysis is able to classify asphalt mixes by gradation – fine, dense mixes such as OCR and SLR display much different graphs than coarse, dense graded mixes such as POW and coarse, open graded mixes such as H174.

As previously introduced, a trough observed in a plot of lacunarity slope indicates the average pattern or texture size for the image. Figure 7.23 displays the MTD versus Average Surface Texture (AST) by specimen type (data from both the core and gyratory top surfaces is presented).

As shown, the AST was highly correlated with MTD. For the gyratory specimens, the relationship is essentially 1-to-1, while for the core specimens the AST was greater than the actual MTD, although excellent correlation was observed ($R^2=0.97$). As shown, the best fit relationships included an intercept parameter, however when the intercept was forced to zero only minor (or no) reduction in fit was observed. Indeed, the intercept values were not statistically significant, which is consistent with the findings of Prowell and Hanson [2005] with the CT Meter.

Recognizing that there is a gap in the MTD data between the dense-graded mixes and the SMA, and that the SMA values were dominating the relationships, AST and MTD for the dense-graded mixes only were plotted in Figure 7.24. As expected, a slight reduction in fit was observed. However, once the intercepts were forced to zero, the linear relationships were quite similar to those when the SMA mix was included (Figure 7.23).

Figure 7.23: Mean Texture Depth versus AST (by Specimen Type)

Figure 7.24: Mean Texture Depth versus AST (no SMA)

The results in Figures 7.23 and 7.24 are very significant because they essentially indicate that the AST determined from lacunarity analysis of the z-vector image is strongly correlated to MTD in a linear fashion valid for both densely and gap-graded mixes. As such, with further data the sand patch test may become redundant.

Based on the specimens tested, Equations 7.18 and 7.19 are presented to estimate field MTD using AST from lacunarity analysis of the PTM z-vector image.

$$MTD_{Field} = C * (Average\ Surface\ Texture_{(Core\ Z-vector)}) \quad [7.18]$$

$$MTD_{Gyratory\ Top} = G * (Average\ Surface\ Texture_{(Gyratory\ Top\ Z-vector)}) \quad [7.19]$$

Where C is a regression constant with a value ranging from 0.53 (dense-graded mixes only with $R^2=0.79$) to 0.60 (all mixes included with $R^2=0.96$) and G is a regression constant ranging from 1.03 (all mixes included with $R^2=0.91$) to 1.09 (dense-graded mixes only with $R^2=0.78$). The range in regression constants is considered small and a single value may be appropriate once additional data is included.

7.8.3 Estimating MTD with Lacunarity Analysis of Standard Images

With the success of the technique to estimate MTD using lacunarity analysis of the PTM Z-vector image, it was considered desirable to determine whether or not lacunarity analysis of a standard image of the pavement surface would provide similar results. This would greatly reduce testing and analysis time by requiring only a single image of the pavement surface to be collected and avoiding PTM analysis.

In reviewing the images collected with the Mark II unit, Light 6 appeared to consistently produce an image whereby the background macrotexture, also referred to as negative texture, was shaded while the positive texture was highlighted (see Figure 7.25). As most of the sand would be captured within the negative texture, it was hoped that lacunarity analysis of the Light 6 images would relate to MTD.

Figure 7.25: Example POW Gyratory Top Imaged Under Light 6

Lacunarity slope for each of the gyratory top specimens was plotted against texture size. As shown in Figure 7.26, the lacunarity slope graphs appeared to characterize the mixes according to gradation (fine, densely graded mix such as DR, coarse, densely graded mix such as POW, and coarse, open-graded mix such as H174).

As with the z-component of the normal vectors, the AST resulting from lacunarity analysis of the Light 6 images were plotted against MTD, although the data was much more spread – particularly for the dense-graded mixes. At this time, the resulting relationships are not sufficiently strong for recommendation. It is possible that slight modification of the lighting angle would improve the results, and this will be recommended for future investigation.

Figure 7.26: Example Lacunarity Slope Graphs of Light 6 Images

7.8.4 Investigating Segregation with Lacunarity Analysis of Standard Images

Although not part of the original investigation, it became apparent during the texture analysis that lacunarity might be able to also investigate segregation of a paved surface. Segregation occurs when the asphalt mix separates into its fine and coarse fractions. When placed and compacted, segregated areas appear either too fine or too coarse with respect to the surrounding surface. Segregation of the mix may occur as a result of poor loading practices from the plant into the trucks, or more commonly as a result of raising wings of the paver during placement. In any event, segregated areas retain rain and meltwater, which accelerates the deterioration of the asphalt and leads to potholes.

At present, the Ontario Ministry of Transportation (MTO) is developing an end result specification for segregation based on MTD as measured with the sand patch test. As lacunarity

analysis investigates texture at all scales within the image, areas of excessive fineness or coarseness should be highlighted.

When reviewing the core and gyratory surfaces, a few of the specimens displayed significant segregation. One such specimen was POW G3T, which displayed excessive coarseness along its right side. When compared to a non segregated surface (POW G1T), the changes in visual texture and lacunarity are evident as shown in Figure 7.27.

Insufficient data was available to pursue this further at this time, however, as lacunarity analysis is able to estimate MTD in the field, the use of the Pavement Surface Imager for segregation analysis appears to be valid. This will be recommended for future investigation.

Figure 7.27: Lacunarity of Segregated (right) and Non-Segregated Surfaces

7.9 Estimating Friction with Image Analysis

7.9.1 Estimating BPN with Lacunarity Analysis of Light 6 Images

As presented in Sections 7.2 and 7.3, relationships developed to relate asphalt mix properties to macrotexture and friction were typically inverse – i.e., factors that positively contributed to macrotexture tended to negatively contribute to friction as measured by the British Pendulum. This is reasonable given that BPN is heavily influenced by microtexture and the provision of less macrotexture increases the contact area of the pendulum shoe and the surface. As such, it was further hypothesized that lacunarity analysis could be used to predict BPN, although lower values were anticipated with increasing average texture.

Lacunarity analysis was conducted on images taken under Light 6 for the gyratory bottom specimens, as these surfaces best correlated with initial field BPN (as represented by the core specimens). Reasonable correlation between AST for the core specimens against initial field BPN (unpolished core specimens) was achieved ($R^2=0.54$) and the graph distinguishes the major gradation categories (refer to Figure A.1 of Appendix A).

The AST for the gyratory bottom specimens was also plotted against average field BPN (core specimens), with much better correlation ($R^2=0.82$) although there are less data points due to the averaging (refer to Figure A.2 or Appendix A).

Based on these initial results, Equations 7.20 ($R^2=0.54$) and 7.21 ($R^2=0.82$) are presented to estimate initial field BPN from AST from lacunarity analysis of the core and gyratory bottom Light 6 images, respectively.

$$BPN_{Initial\ Field} = 63.65 - 3.64 * (Average\ Surface\ Texture_{(Core\ Light\ 6)}) \quad [7.20]$$

$$BPN_{Initial\ Field} = 65.69 - 6.67 * (Average\ Surface\ Texture_{(Gyratory\ Bottom\ Light\ 6)}) \quad [7.21]$$

Lacunarity analysis was then completed on the core and gyratory bottom specimens imaged with Light 6 at all levels of polish to determine whether the Mark II unit could also replace the British Pendulum Test.

Unfortunately, the use of AST from lacunarity analysis of the Light 6 image does not appear to be sensitive enough to predict the changes in BPN between the initial and low polish states (refer to Figure A.3 in Appendix A). Whereas one might expect the AST to decrease with increasing friction due to the exposure of smaller microtexture particles, this was not observed. Indeed, the dataset became more scattered. Analysis of the medium and high polish levels was therefore not completed on the Light 6 images.

7.9.3 Estimating BPN with Lacunarity Analysis of PTM Z-Vector Images

Although reasonable correlation was observed between AST from the Light 6 images and BPN, the same analysis was conducted on the PTM Z-Vector images to determine whether better predictive power could be achieved.

The AST for the core specimens was plotted against initial field BPN (core specimens), with a slight improvement in correlation achieved ($R^2=0.55$) when compared to the Light 6 results (refer to Figure A.4 in Appendix A). The AST for the gyratory bottom specimens against average field BPN (core specimens) provided better correlation ($R^2=0.76$) but not as high as that achieved with the Light 6 images (see Figure A.5). Again, there are less data points due to the averaging.

Based on these results, Equations 7.22 ($R^2=0.55$) and 7.23 ($R^2=0.77$) are presented to estimate initial field BPN from AST from lacunarity analysis of the core and gyratory bottom PTM Z-vector images, respectively.

$$BPN_{Initial\ Field} = 65.04 - 7.04 * (Average\ Surface\ Texture_{(Core\ Z-Vector)}) \quad [7.22]$$

$$BPN_{Initial\ Field} = 67.44 - 14.68 * (Average\ Surface\ Texture_{(Gyratory\ Bottom\ Z-Vector)}) \quad [7.23]$$

Lacunarity analysis was then completed on the core and gyratory bottom specimens Z-vector images at all levels of polish to determine whether the Mark II unit could also replace the British Pendulum Test.

Unfortunately, as observed with the Light 6 analysis, the use of AST does not appear to be sensitive enough to predict the changes in BPN between the initial, low or high polish states. When the datasets were combined, the resulting relationship R^2 dropped significantly from 0.52 to 0.37. The data was too scattered for accurate prediction of BPN (see Figure A.6).

7.10 Summary of Database Resulting from Analysis Effort

The data analysis effort resulted in the development of 23 new relationships and 43 figures relating asphalt mix properties, texture, friction and image parameters – with numerous conclusions that will be presented in Section 8.0. These new and valuable relationships were the result of over 175 statistical comparisons, 186 lacunarity analyses, and countless data fitting exercises conducted in a stepwise (but often trial and error) fashion.

CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

8.1 Chapter Objective

The objective of Chapter 8 is to consolidate the findings reported in Chapter 7 into a set of useful conclusions that may be either immediately used by the asphalt and/or pavement engineering community, or subjected to further investigation during future research efforts.

8.2 Optimizing Pavement Friction and Texture at the Mix Design Stage

The comprehensive field and laboratory sampling and testing programs completed during this research have provided numerous and valuable insights into the contribution of asphalt mix properties toward as-constructed pavement texture and friction. With this knowledge and the series of models developed, designers may introduce friction and texture as mix design variables similar to Marshall stability, flow, Superpave gyration levels, air voids, VMA, etc.

The following conclusions have been drawn for this investigation concerning measurement and prediction of texture and friction for mix design purposes:

- i) The top and bottom surfaces of asphalt specimens created in the Superpave gyratory compactor yield different results with respect to macrotexture (from the sand patch test) and friction (from the British Pendulum Test). Detailed investigation as to the cause of these differences was not part of the current investigation, however, there is a different confinement regime in the bottom of the gyratory mould as compared to the top. Segregation of the mix during specimen preparation may also be involved.
- ii) With respect to conclusion i), the gyratory top surface consistently provided 40 to 42% greater macrotexture (Mean Texture Depth) as compared to the gyratory bottom surface.

- iii) The gyratory top surface best simulates the as-constructed pavement surface with respect to macrotexture (MTD). When all mixes were included, a polynomial relationship as per Equation 7.3 ($R^2=0.99$) was appropriate, however, the dense-graded mixes were best represented with a linear relationship as per Equation 7.4 ($R^2=0.72$).

$$MTD_{Field} = 1.14(MTD_{Top})^2 - 0.81(MTD_{Top}) + 0.40 \quad [7.3]$$

$$MTD_{Field} = 0.52(MTD_{Top}) + 0.05 \quad [7.4]$$

Given the considerable gap in MTD data between 0.5 and 1.6 mm, engineering judgement must be used when estimating field MTD from gyratory top surfaces. However, given the costs and safety risks associated with field testing, it is considered worthwhile to get an estimate from the gyratory surfaces.

- iv) Macrotexture measured in the field using a laser texture sensor (Mean Profile Depth) was related to core MTD through a well behaved linear relationship as per Equation 7.5. The relationship was the same whether all mixes were included ($R^2=0.99$), or just the dense-graded mixes ($R^2=0.81$) and indicated that MPD values were approximately 86% greater than MTD values for the same surface.

$$MPD_{Field} = 1.86(MTD_{Core}) \quad [7.5]$$

This result is somewhat different than the existing ASTM standard E1845, which provides a linear relationship between MPD and MTD as per Equation 7.6 (rearranged for MPD).

$$MPD_{Field} = 1.25(MTD_{Core}) - 0.01 \quad [7.6]$$

With respect to conclusion iv), field MPD was related to gyratory top surface MTD through a polynomial relationship when all mixes were included and a linear

relationship when only the dense-graded mixes were included. At this time, the resulting relationships are considered too weak for estimating field MPD from sand patch testing of gyratory top surfaces.

- v) Significant differences in MPD at initial construction and after 1 year in service were not observed (nor expected).
- vi) With respect to conclusions i) and ii), the gyratory top surface yielded increased friction (British Pendulum Number) as compared to the gyratory bottom surface due to crushing of the surface aggregate during compaction, which exposed additional microtexture.
- vii) As a result of the crushing of surface aggregates in the gyratory compactor (conclusion vi), the gyratory top surfaces were statistically different than the field core surfaces. Through a series of ANOVA, Tukey and Dunnett comparison tests, it was determined that the gyratory bottom surface was statistically the same as the field cores and therefore British Pendulum testing of the gyratory bottom surface can be used to predict the initial friction of densely-graded pavement surfaces. This finding was independent of polishing level so long as the core and gyratory bottom specimen received the same level of polish.
- viii) The only exception to conclusion vii) was the coarse SMA mixture. Neither the gyratory top nor bottom surfaces matched well with the respective core surfaces. As such, it is concluded that laboratory specimens cannot be used to predict the as-constructed friction (BPN) of gap-graded mixes such as SMA.
- ix) The initial friction (BPN) of the tested mixes was not necessarily improved with the use of premium, polish-resistant aggregates over limestone aggregates, as much of the microtexture was initially coated with asphalt cement.

- x) One notable exception to conclusion ix) was the addition of Manufactured Shingle Modifier (MSM), which although only comprising 3% of the mix by weight, greatly increased the initial friction of mixes containing limestone aggregates. MSM may therefore be used as a cost effective additive for improving pavement friction as compared to the use of premium aggregates. To the author's knowledge, this is the first study to observe the substantial gain in BPN as a result of the use of MSM.
- xi) Friction (BPN) of the core and gyratory bottom specimens was greatly increased from the initial as-constructed state through the application of a low number of polishing cycles (10) with sandpaper to remove the asphalt film from the surface aggregates. BPN for the limestone mixes increased by 15%, while mixes containing premium coarse aggregate or MSM displayed an increase in BPN of 13.6%. The SMA mixture observed the greatest increase in BPN at low polishing (22.4%) as its microtexture was exposed beneath the thick asphalt cement film.
- xii) Increased polishing effort to 30 cycles generally resulted in a significant reduction in friction (BPN) from the low polish state (10 cycles), however further polishing effort (80 cycles) did not result in a significant loss in BPN and in many cases the friction returned to as-constructed levels. As noted by previous research [Emery 1982], it appears that long term friction stabilizes through an equilibrium between polishing and microtexture refreshment under trafficking.
- xiii) Macrottexture (MTD or MPD) of the as-constructed pavement surface was related to mix properties. Specifically, macrottexture was sensitive to fineness modulus (FM), voids in the mineral aggregate (VMA), percent passing the 4.75 mm sieve ($P_{4.75}$), coefficient of curvature (C_c), asphalt cement content ($\%AC$), percent passing the 0.075 mm sieve ($\%Dust$), and compaction level (bulk relative density, BRD).

Numerous combinations and transforms of these properties were evaluated, however, given the data gap between 0.6 and 1.4 mm MTD, definitive models cannot be concluded at this time.

- xiv) Initial friction (BPN) of the as-constructed pavement surface was also sensitive to mix properties. Interestingly, similar variables that were the most influential toward macrotexture were also the most influential toward friction, however, their respective affects were inverted such that reducing the factors that increased macrotexture resulted in increased friction.
- xv) With respect to conclusion xiv), because there were no significant data gaps in the BPN data, a model for predicting initial friction from mix properties was developed. The logarithmic relationship shown in Equation 7.15 provides reasonable prediction ($R^2=0.66$) of initial BPN from mix properties without excessive data clustering. As shown, initial field friction as measured with the British Pendulum (a surrogate for microtexture) was most sensitive to changes in dust to binder ratio and coefficient of curvature.

$$BPN_{InitialField} = 52.9 + 3.6 * \left(\frac{DBR}{Cc} \right) \quad [7.15]$$

Additional data is required for validation of this model, however and laboratory testing of cores (or gyratory bottom surfaces) is recommended as a more direct method of estimating field friction.

8.3 Replace the Sand Patch Test with the Pavement Surface Imager?

Provision of adequate macrotexture is a key component to draining excess surface water and avoid hydroplaning. Although the sand patch test is widely used and inexpensive, it requires considerable time to complete and therefore increases the risk of harm to the tester while in the lane closure. High speed laser sensors are able to collect data at highway speed and therefore eliminate risk of operator injury, however they are expensive to purchase and do not appear to provide reliable data for use with the International Friction Index (IFI).

The Pavement Surface Imager was developed as a rapid, low cost, portable data acquisition and analysis system based upon digital imaging techniques to objectively assess pavement frictional and texture properties under in both rural and urban environments, as well as in the laboratory for forensic and mix design purposes.

The results of this research have provided the foundation for an image-based analysis technique to replace both the sand patch test and expensive laser-based texture devices with the Pavement Surface Imager. Specific conclusions made during the investigation in this regard include:

- xvi) First order grey level statistics such as fractal dimension, aspect, slope, diversity, curvature, relative richness, etc. calculated on a selection of scanned Schonfeld images were not able to predict the Schonfeld texture parameters (or skid number).
- xvii) Second order grey level statistics based on co-occurrence matrices such as Angular Second Moment, Contrast, Entropy, etc. were also unable to predict the Schonfeld texture parameters (or skid number).
- xviii) Semivariance analysis was also unable to provide significant relationships between the Schonfeld images and texture parameters (or skid number).

- xix) Lacunarity analysis of the Schonfeld images was sensitive to different pavement surfaces and was carried forward for analysis of images taken with the Pavement Surface Imager.
- xx) Analysis of the Schonfeld images in 3 dimensions was unsuccessful as the available software was unable to generate a digital elevation model (DEM) from the scanned stereographs.
- xxi) Extraction of a DEM from images taken with the Mark I Pavement Surface Imager using the Photometric Stereo Method (PSM) as proposed by Kim and Burger [1991] was unsuccessful. Additional lights were added (Mark II Pavement Surface Imager) to allow Polynomial Texture Mapping (PTM) analysis and surface normal vectors of each pixel were successfully derived.
- xxii) Numerical integration of the surface normal vectors to derive a DEM was then attempted, but unsuccessful due to noted limitations of the integration techniques utilized.
- xxiii) Notwithstanding conclusion xxii), lacunarity analysis of the z-component of the surface normal vector at each pixel provided excellent correlation to MTD when all mixes were included, as well as when evaluating only the dense-graded mixes. Specifically, the Average Surface Texture (AST) size of the Z-vector image determined from lacunarity analysis was directly related to MTD using Equation 7.18 for core specimens or Equation 7.19 for the gyratory top specimen.

$$MTD_{Field} = C * (Average Surface Texture_{(Core Z-vector)}) \quad [7.18]$$

$$MTD_{GyratoryTop} = G * (Average Surface Texture_{(Gyratory Top Z-vector)}) \quad [7.19]$$

For the core specimens, regression constant C ranged from 0.53 for the dense-graded mixes ($R^2=0.79$) to 0.60 when all mixes were included ($R^2=0.96$). For the

gyratory top surfaces, regression constant G ranged from 1.03 when all mixes were included ($R^2=0.91$) to 1.09 for the dense-graded mixes alone ($R^2=0.78$). Despite the macrotexture data gap, the range in these regression constants (by specimen type) are considered small and a single value may be appropriate once additional data becomes available.

xxiv) Lacunarity analysis of a single image (as illuminated by Light 6) was attempted to determine whether macrotexture could be estimated with less input data than required to generate surface normal vectors. The relationship between field macrotexture and the resulting AST from the Light 6 image was not considered strong enough for predictive purposes.

xxv) Limited investigation also suggested that lacunarity analysis may be used to quantify segregation of a pavement surface. Additional investigation is warranted in this area.

8.4 Replace the British Pendulum Test with the Pavement Surface Imager?

Like the sand patch test, the British Pendulum Test is widely used and relatively inexpensive. However, it suffers from the same issues - it requires considerable time to complete and therefore increases the risk of harm to the tester while in the lane closure. High speed friction systems are able to collect data at highway speed and therefore eliminate risk of operator injury, however they are very expensive to purchase and maintain.

This research effort has indicated that asphalt mix properties related to macrotexture are also typically related to friction, although their contribution was inverse. It was therefore hoped that the success observed relating AST from lacunarity analysis to MTD would translate to BPN as well. Indeed, an inverse relationship was observed – reduction in AST was characteristic of increased friction, however the correlation was much less than observed during macrotexture analysis, particularly when investigating pavement surfaces that have received polishing effort. Therefore, at this time it seems that the Mark II Pavement Surface Imager is not able to replace the British Pendulum Test for friction measurement, most likely due to the inability of current integration techniques to derive 3-dimensional DEMs. Specific conclusions made during the investigation in this regard include:

- xxvi) The AST of the z-vector image determined from lacunarity analysis was related to initial BPN of the core specimens through Equation 7.22 ($R^2=0.55$) and the gyratory bottom specimens through Equation 7.23 ($R^2=0.77$).

$$BPN_{Initial\ Field} = 65.04 - 7.04 * (Average\ Surface\ Texture_{(Core\ Z-Vector)}) \quad [7.22]$$

$$BPN_{Initial\ Field} = 67.44 - 14.68 * (Average\ Surface\ Texture_{(Gyratory\ Bottom\ Z-Vector)}) \quad [7.23]$$

- xxvii) When BPN values at different levels of polish were introduced to the dataset, a similar relationship between AST from the z-vector image and BPN was observed,

however the predictive power of the relationship was reduced ($R^2=0.37$). As such, lacunarity analysis does not appear sensitive enough to predict changes in BPN with polishing.

xxviii) Lacunarity analysis of the Light 6 images alone was also related to initial BPN with more success than observed with the macrotexture data. The initial BPN may be estimated from the AST from lacunarity analysis of the Light 6 image as presented in Equations 7.20 ($R^2=0.54$) and 7.21 ($R^2=0.82$).

$$BPN_{Initial Field} = 63.65 - 3.64*(Average Surface Texture_{(Core Light 6)}) \quad [7.20]$$

$$BPN_{Initial Field} = 65.69 - 6.67*(Average Surface Texture_{(Gyratory Bottom Light 6)}) \quad [7.21]$$

However, when BPN values at different levels of polish were introduced, the relationships presented in Equations 7.20 and 7.21 became more scattered. As such, lacunarity analysis of the Light 6 images alone does not appear sensitive enough to predict changes in BPN with polishing.

8.5 Contribution to Existing Knowledge

With reference to Section 1.7, this section provides a summary of the three major contributions resulting from this investigation.

First, this was the first known investigation to statistically compare the specimen surfaces (top and bottom) produced in the gyratory compactor to as-constructed field surfaces with respect to friction and texture measurement. Furthermore, new and powerful relationships have been developed to estimate friction and texture based on mix properties. This contribution will be extremely valuable to pavement and mix designers, as they will be able to not only modify the mix properties to optimize friction and texture in the laboratory, but also directly (and

confidently) determine the anticipated field properties without the need for costly trial sections or exposing technical staff to the hazards associated with field testing.

Second, this investigation involved the development of an inexpensive, rapid, and portable digital imaging system that may be used both in the laboratory and field for documenting pavement surfaces. The images collected with the system provide both immediate characterization of surface friction and texture, as well as provide an archive for future analysis – a feature not provided by other test methods.

Finally, novel application of Polynomial Texture Mapping allowed the generation of a surface normal vector map of the pavement surface at the microtexture scale. Analysis of the surface normal map, as well as one of the strategically selected images using lacunarity provided the dominant particle size of the surface, which was then directly and accurately related to the Mean Texture Depth (MTD) provided by the traditional sand patch test (ASTM E965). This new "digital" sand patch test may be completed up to 10 times faster than a traditional sand patch test, thereby allowing a greater number of areas to be evaluated, or dramatically reducing the amount of time (therefore cost and risk) in which the technician is in the field, or both.

8.6 Recommendations for Future Work

Creation of digital elevation models (DEMs) of pavement surfaces at close range remains of primary interest, as it is anticipated that 3-dimensional analysis will provide even better prediction of pavement texture and friction than observed during this investigation. To this end, the following recommendations are provided:

- a) Collaborate with researchers at the University of Manitoba who have developed a method to derive elevation models through integration of surface normal vector maps.

- b) The use of 10 lighting positions for PTM analysis provides the opportunity to conduct PSM analysis with multiple combinations of 4 lights. In other words, values of depth could be solved at each pixel location using different combinations of 4 of the 10 available lights. This analysis would be more robust because of the added redundancy.
- c) A Mark III Pavement Surface Imager could be developed to collect digital stereographs, as well as images for PTM analysis, recognizing the inherent issues associated with digital photogrammetry such as correspondence.

Furthermore, the results obtained between mix properties, AST from lacunarity analysis, and macrotexture (MTD and MPD) should be built upon, as follows:

- d) There is a need to evaluate mixes with macrotexture in the range of 0.6 to 1.4 mm (MTD) to fill in the existing data gap. This macrotexture range would likely be provided with a 9.5 mm SMA or an HL4 mixture (16 mm nominal).
- e) Use of lacunarity analysis should be extended to investigate and quantify asphalt pavement segregation, which currently relies on sand patch testing. The Mark II Pavement Surface Imager could be used to rapidly compare segregated and non-segregated areas for quality control and assurance purposes.
- f) Although Light 6 of the Mark II unit appeared to best shadow areas of negative texture related to MTD and highlight texture related to friction, it is likely that further investigation of lighting angle would reveal a more optimum location.

Finally, the considerable image library amassed during this investigation may be regularly revisited as new and novel analysis techniques become available.

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APPENDIX 1 – SAND PATCH AND BRITISH PENDULUM TEST RESULTS

Medium Polishing	19.4	Core 1-1-3	67.5	67	67	67	67	67.1	67.1										
	19.5	Core 1-1-4	62	62.5	64	64	64	63.1	63.1										
	19.6	Core 1-1-5	70	70	70	70	70	70.0	70.0										
	19.8	Core 1-1-6	65	66	65	65	64	65.0	65.1										
	17.6	Gyratory 1 - Bottom	67.5	67	67.5	67.5	67.5	67.4	66.5										
	17.5	Gyratory 1 - Top	70	70	70	70	69	69.8	68.8										
	17.6	Gyratory 2 - Bottom	66	67.5	68	66	66	66.9	66.0										
	17.6	Gyratory 2 - Top	77	77	77	77	77	77.0	76.1										
	17.6	Gyratory 3 - Bottom	67	67	67	67	67	67.0	66.1										
	17.7	Gyratory 3 - Top	72	72	71	72	72	71.8	70.9										
	20.3	Core 1-1-1	60	60	61	60	60	60.3	60.6										
	20	Core 1-1-3	62	60	61	62	62	61.3	61.4										
	19.9	Core 1-1-4	59	60	59	60	60	59.5	59.7										
	19.9	Core 1-1-5	65	64	65	64	64	64.5	64.7										
High Polishing	20	Core 1-1-6	61	60	62	60	60	60.8	60.9										
	18.5	Gyratory 1 - Bottom	64	65	63	63	63	63.8	63.3										
	18.6	Gyratory 1 - Top	67.5	67.5	68	69	69	68.0	67.6										
	18.2	Gyratory 2 - Bottom	62	60	60	62	62	61.0	60.4										
	18.3	Gyratory 2 - Top	68	68	68	67.5	67.5	67.9	67.3										
	17.9	Gyratory 3 - Bottom	61	60	62	60	60	60.8	60.0										
	18	Gyratory 3 - Top	66	66	65	67.5	67.5	66.1	65.4										

COMMENTS: *Mean BPN value is temperature corrected to 20C automatically. Individual BPN values are those recorded during the test.

Master British Pendulum and Sand Patch Test Results

Road:

RR

Mix Type:

HL1 Modified

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	1	2	3	4	MEAN BPN	TEMP CORR BPN*	Sand Volume (mL)	Sand Patch Diameter (mm)	Mean Texture Depth (mm)	Notes
No Polishing	19	Core 1-1-1	58	57.5	57	57.5	57.5	57.2	5.0	105.3	0.57	Tested June 19, 2005
		Core 1-1-2	54	52.5	52	52.5	52.8	52.5	5.0	125.8	0.40	Tested June 19, 2005
		Core 1-1-3	54	54	52.5	52	53.1	52.9	5.0	115.3	0.48	Tested June 19, 2005
		Core 1-1-4	58	56	55	55	56.0	55.7	5.0	124.0	0.41	Tested June 19, 2005
		Core 1-2-1	57.5	57.5	57	56.5	57.1	56.9	5.0	113.8	0.49	Tested June 19, 2005
		Core 1-2-2	57.5	57	55.5	55.5	56.4	56.1	5.0	122.3	0.43	Tested June 19, 2005
		Gyratory 1 - Bottom	55	55	55	54.5	54.9	54.6	5.0	124.25	0.41	Tested June 19, 2005
		Gyratory 1 - Top	70	70.5	70.5	72	70.8	70.5	5.0	92.8	0.74	Retested July 3, 2005
		Gyratory 2 - Bottom	54.5	54	54.5	53.5	54.1	53.9	5.0	119.5	0.45	Tested June 19, 2005
		Gyratory 2 - Top	71	71	70	70	70.5	70.2	5.0	95.3	0.70	Tested June 19, 2005
		Gyratory 3 - Bottom	52.5	52.5	52	53.5	52.6	52.4	5.0	124.3	0.41	Tested June 19, 2005
		Gyratory 3 - Top	69.5	70	70.5	72	70.5	70.2	5.0	94.8	0.71	Retested July 3, 2005
		Gyratory 4 - Bottom	63.5	63	62.5	62.5	62.9	62.6	5.0	108.8	0.54	Tested June 19, 2005
		Gyratory 4 - Top	72	72	71.5	70	71.4	71.1	5.0	95.3	0.70	Tested June 19, 2005
		Gyratory 5 - Bottom	57.5	58	57.5	58.5	57.9	57.6	5.0	105.8	0.57	Tested June 19, 2005
		Gyratory 5 - Top	70	70	70.5	69	69.9	69.6	5.0	90.5	0.78	Tested June 19, 2005
		Gyratory 6 - Bottom	57.5	57.5	57.5	57.5	57.5	57.2	5.0	109.0	0.54	Tested June 19, 2005
		Gyratory 6 - Top	69	68	67.5	67.5	68.0	67.7	5.0	92.5	0.74	Tested June 19, 2005
		Gyratory 7 - Bottom	65	64.5	64.5	63.5	64.4	64.1	5.0	105.5	0.57	Tested June 19, 2005
		Gyratory 7 - Top	71.5	70	70.5	70	70.5	70.2	5.0	91.0	0.77	Tested June 19, 2005
	19	Core 1-1-1	71	71	70	71	70.8	70.5				Tested Jan. 9, 2008
	18.5	Core 1-1-2	72	72	74	72.5	72.6	72.1				
	18.4	Core 1-1-3	69	68	68	67.5	68.1	67.6				

	18.7	Gyratory 5 - Top	69	67.5	67	69	68.1	67.7					
	18.8	Gyratory 6 - Bottom	60	60	62	60	60.5	60.2					
	18.8	Gyratory 6 - Top	70	69	71	69	69.8	69.4					
	17.5	Gyratory 7 - Bottom	67	65	65	66	65.8	64.8					
	17.6	Gyratory 7 - Top	70	70	70	70	70.0	69.1					
	20.5	Core 1-1-1	59	60	60	58	59.3	59.7					
	20.5	Core 1-1-2	52	53	51	51	51.8	52.2					
	20.4	Core 1-1-3	48	49	51	50	49.5	49.9					
	20.3	Core 1-1-4	54	52.5	52.5	54	53.3	53.6					
	20.8	Core 1-2-1	52	52	54	51	52.3	52.8					
	20.5	Core 1-2-2	53	52.5	52.5	51	52.3	52.7					
	18.8	Gyratory 1 - Bottom	57	55	57.5	58	56.9	56.5					
	18.6	Gyratory 1 - Top	62	60	61	61	61.0	60.6					
	18.6	Gyratory 2 - Bottom	56	56	58	57	56.8	56.3					
	18.6	Gyratory 2 - Top	72	72.5	72.5	71	72.0	71.6					
	18.6	Gyratory 3 - Bottom	57	57	58	57	57.3	56.8					
	18.6	Gyratory 3 - Top	72	71	70	70	70.8	70.3					
	18.7	Gyratory 4 - Bottom	68	68	66	67	67.3	66.9					
	18.9	Gyratory 4 - Top	71	71	71	71	71.0	70.7					
	19	Gyratory 5 - Bottom	62	61	62	62	61.8	61.5					
	19.1	Gyratory 5 - Top	62	62	63	62.5	62.4	62.2					
	19	Gyratory 6 - Bottom	61	60	59	61	60.3	60.0					
	21.1	Gyratory 6 - Top	68	69	67	67	67.8	68.4					
	17.8	Gyratory 7 - Bottom	62.5	62	62	62	62.1	61.3					
	18	Gyratory 7 - Top	68	70	69	68	68.8	68.0					
High Polishing													

COMMENTS: *Mean BPN value is temperature corrected to 20C automatically. Individual BPN values are those recorded during the test.

Master British Pendulum and Sand Patch Test Results

Road:

UDHS

Mix Type:

Superpave 12.5mm

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	1	2	3	4	MEAN BPN	TEMP CORR BPN*	Sand Volume (mL)	Sand Patch Diameter (mm)	Mean Texture Depth (mm)	Notes
No Polishing	19	Core 1	62	61.5	60.5	60	61.0	60.7	1.7	75.8	0.37	Tested June 19, 2005
		Core 2	61	61	59	59.5	60.1	59.9	1.7	87.8	0.28	Tested June 19, 2005
		Core 3	60.5	59.5	59	58.5	59.4	59.1	1.7	92.5	0.25	Tested June 19, 2005
		Core 4	60	60	59.5	58	59.4	59.1	1.7	85.3	0.29	Tested June 19, 2005
		Gyratory 1 - Bottom	65	65.5	64.5	63	64.5	64.2	5.0	125	0.41	Tested June 19, 2005
		Gyratory 1 - Top	70	69	68.5	69	69.1	68.9	5.0	97.8	0.67	Tested June 19, 2005
		Gyratory 2 - Bottom	64.5	64.5	62	62	63.3	63.0	5.0	130.3	0.38	Tested June 19, 2005
		Gyratory 2 - Top	72.5	73	72	72	72.4	72.1	5.0	108.0	0.55	Tested June 19, 2005
		Gyratory 3 - Bottom	65	65.5	65	65	65.1	64.9	5.0	134.5	0.35	Tested June 19, 2005
		Gyratory 3 - Top	69	69.5	70.5	72	70.3	70.0	5.0	106.3	0.56	Retested July 3
Low Polishing	19.6	Core 1	66	65	65	67	65.8	65.8				
	19.3	Core 2	70	70	70	70	70.0	69.9				
	19.6	Core 3	70	69	69	69	69.3	69.3				
	19.1	Core 4	68	68	68	66	67.5	67.3				
	18.4	Gyratory 1 - Bottom	72	72	70	71	71.3	70.7				
	18.2	Gyratory 1 - Top	70	70	70	70	70.0	69.4				
	18.3	Gyratory 2 - Bottom	72	72	71	70	71.3	70.7				
	18.3	Gyratory 2 - Top	72.5	72.5	72	72	72.3	71.7				
	18.6	Gyratory 3 - Bottom	67	67.5	67	67.5	67.3	66.8				
	18.5	Gyratory 3 - Top	74	72.5	72.5	72.5	72.9	72.4				
	19.9	Core 1	68	69	67	68	68.0	68.2				
	19.9	Core 2	68	68	68	68	68.0	68.2				
	19.7	Core 3	67	68	67	68	67.5	67.6				

Medium Polishing	19.3	Core 4	65	67	67	65	66.0	65.9				
	19	Gyratory 1 - Bottom	65	66	65	65	65.3	65.0				
	19	Gyratory 1 - Top	67.5	67.5	67.5	65	66.9	66.6				
	18.6	Gyratory 2 - Bottom	66	66	65	64	65.3	64.8				
	18.6	Gyratory 2 - Top	66	67.5	67	66	66.6	66.2				
	18.3	Gyratory 3 - Bottom	64	64	65	64	64.3	63.7				
	18.5	Gyratory 3 - Top	65	65	67	67	66.0	65.5				
	20.1	Core 1	72	73	72	71	72.0	72.2			#DIV/0!	
High Polishing	20.3	Core 2	66	66	67	66	66.3	66.6			#DIV/0!	
	20.3	Core 3	67	65	67	66	66.3	66.6			#DIV/0!	
	20.2	Core 4	70	69	69	69	69.3	69.5			#DIV/0!	
	19.6	Gyratory 1 - Bottom	66	66	65	64	65.3	65.3			#DIV/0!	
	19.5	Gyratory 1 - Top	65	65	67	67	66.0	66.0			#DIV/0!	
	19.2	Gyratory 2 - Bottom	62	61	63	61	61.8	61.6			#DIV/0!	
	19.6	Gyratory 2 - Top	66	66	68	67	66.8	66.8			#DIV/0!	
	19	Gyratory 3 - Bottom	63	62	64	62	62.8	62.5			#DIV/0!	
	19	Gyratory 3 - Top	66	65	66	66	65.8	65.5			#DIV/0!	

COMMENTS: *Mean BPN value is temperature corrected to 20C automatically. Individual BPN values are those recorded during the test.

Master British Pendulum and Sand Patch Test Results

Road:

UDH3

Mix Type:

HL3

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	1	2	3	4	MEAN BPN	TEMP CORR BPN*	Sand Volume (mL)	Sand Patch Diameter (mm)	Mean Texture Depth (mm)	Notes
No Polishing	19	Core 1	65	65	64	64.5	64.6	64.4	1.7	79.8	0.33	Tested June 19, 2005
		Core 2	59	59.5	58.5	59	59.0	58.7	1.7	88.0	0.27	
		Core 3	62	62	60	59	60.8	60.5	1.7	91.8	0.25	
Low Polishing	18.7	Core 1	74	74	72.5	72.5	73.3	72.9				Tested Jan. 6, 2008
	18.7	Core 2	70	70	69	68	69.3	68.9				
	18.7	Core 3	70	69	70	70	69.8	69.4				
Medium Polishing	19.8	Core 1	69	70	70	69	69.5	69.6				Tested Jan. 15, 2008
	19.1	Core 2	67.5	69	67	67	67.6	67.4				
	19.4	Core 3	67	67	66	65	66.3	66.2				
High Polishing	20.6	Core 1	70	69	69	70	69.5	70.0			#DIV/0!	
	20.3	Core 2	67	66	65	65	65.8	66.1			#DIV/0!	
	20.1	Core 3	66	66	66	65	65.8	66.0			#DIV/0!	

COMMENTS:

*Mean BPN value is temperature corrected to 20C automatically. Individual BPN values are those recorded during the test.

Master British Pendulum and Sand Patch Test Results

Road:

H174

Mix Type:

12.5mm SMA

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	1	2	3	4	MEAN BPN	TEMP CORR BPN*	Sand Volume (mL)	Sand Patch Diameter (mm)	Mean Texture Depth (mm)	Notes
No Polishing	19	Core 1-2-1	49.5	48	47	47.5	48.0	47.7	10.0	88.8	1.62	Tested June 19, 2005
		Core 1-2-3	55	54.5	52.5	52.5	53.6	53.4	10.0	85.5	1.74	
		Core 1-2-4	53	52.5	52	52	52.4	52.1	10.0	82.0	1.89	
		Core 1-3-1	47.5	48	47.5	47.5	47.6	47.4	10.0	94.5	1.43	
		Core 1-3-2	48	47	45.5	45.5	46.5	46.2	10.0	94.5	1.43	
		Core 1-3-3	37.5	37.5	37	37	37.3	37.0	10.0	92.8	1.48	
		Gyratory 1 - Bottom	68	68	67.5	67.5	67.8	67.5	10.0	130.75	0.75	
		Gyratory 1 - Top	68	67.5	66	66	66.9	66.6	10.0	106.8	1.12	
		Gyratory 2 - Bottom	73	72	71	71	71.8	71.5	10.0	106.0	1.13	
		Gyratory 2 - Top	64	64	63	63	63.5	63.2	10.0	87.0	1.68	
		Gyratory 3 - Bottom	73	73	71	71	72.0	71.7	10.0	119.5	0.89	
		Gyratory 3 - Top	69	70.5	69.5	68	69.3	69.0	10.0	91.3	1.53	
		Gyratory 4 - Bottom	72.5	71	73.5	72.5	72.4	72.1	10.0	108.3	1.09	
		Gyratory 4 - Top	67.5	68.5	66	66	67.0	66.7	10.0	95.0	1.41	
		Gyratory 5 - Bottom	72	74	73	71	72.5	72.2	10.0	98.3	1.32	
		Gyratory 5 - Top	69.5	72	70	69.5	70.3	70.0	10.0	82.5	1.87	
		Gyratory 6 - Bottom	67.5	68	67	67.5	67.5	67.2	10.0	97.3	1.35	
		Gyratory 6 - Top	70.5	72.5	70.5	71	71.1	70.9	10.0	83.5	1.83	
	19.1	Core 1-2-1	60	61	62	60	60.8	60.5				
	19.6	Core 1-2-3	62	62.5	62.5	62	62.3	62.3				
	19.6	Core 1-2-4	55	53	55	54	54.3	54.3				
	19.6	Core 1-3-1	55	55	54	54	54.5	54.5				
	19.6	Core 1-3-2	55	55	56	54	55.0	55.0				

High Polishing	20.4	Core 1-2-3	56	56	57	58	56.8	57.1					
	20.5	Core 1-2-4	47	48	48	47	47.5	47.9					
	20.9	Core 1-3-1	51	52	50	51	51.0	51.6					
	21	Core 1-3-2	50	49	49	47.5	48.9	49.5					
	20.9	Core 1-3-3	52	52	50	52.5	51.6	52.2					
	19.3	Gyratory 1 - Bottom	62	62	62	62	62.0	61.9					
	19.3	Gyratory 1 - Top	65	66	67	67	66.3	66.1					
	19	Gyratory 2 - Bottom	70	71	72.5	72	71.4	71.1					
	19.1	Gyratory 2 - Top	67	67	68	68	67.5	67.3	Could also be (58, 58, 59, 60)				
	18.9	Gyratory 3 - Bottom	70	70	70	69	69.8	69.5					
	18.9	Gyratory 3 - Top	68	65	66	66	66.3	66.0					
	18.5	Gyratory 4 - Bottom	69	68	70	67	68.5	68.0					
	18.4	Gyratory 4 - Top	73	73	74	73	73.3	72.7					
	18.3	Gyratory 5 - Bottom	61	60	60	62	60.8	60.2					
	18.6	Gyratory 5 - Top	69	69	70	70	69.5	69.1					
	18.4	Gyratory 6 - Bottom	62	62	63	61	62.0	61.5					
	17.8	Gyratory 6 - Top	67	69	67.5	68	67.9	67.1					

COMMENTS: *Mean BPN value is temperature corrected to 20C automatically. Individual BPN values are those recorded during the test.

	17.6	Gyratory 2 - Bottom	72	71	72.5	71	71.6	70.7				
	17.8	Gyratory 2 - Top	70	70	71	71	70.5	69.7				
	17.5	Gyratory 3 - Bottom	75	75	75	74	74.8	73.8				
	17.6	Gyratory 3 - Top	67	68	67	68	67.5	66.6				
High Polishing	20.1	Core 1	66	66	66	65	65.8	66.0				#DIV/0!
	20	Core 2	65	64	65	66	65.0	65.2				#DIV/0!
	20	Core 3	65	63	63	64	63.8	63.9				#DIV/0!
	18.6	Gyratory 1 - Bottom	70	69	70	68	69.3	68.8				#DIV/0!
	18.4	Gyratory 1 - Top	70	71	72	71	71.0	70.5	(could be 66, 66, 66, 65)			#VALUE!
	18.1	Gyratory 2 - Bottom	68	67.5	66	68	67.4	66.7				#DIV/0!
	18	Gyratory 2 - Top	68	69	69	70	69.0	68.3				#DIV/0!
	18	Gyratory 3 - Bottom	72	72	71	70	71.3	70.5				#DIV/0!
	18	Gyratory 3 - Top	70	70	70	72	70.5	69.8				#DIV/0!

COMMENTS: *Mean BPN value is temperature corrected to 20C automatically. Individual BPN values are those recorded during the test.

**During Medium polishing, a lot of fine debris was created as the aggregate particles were chipped away.

Master British Pendulum and Sand Patch Test Results

Road:

OCR

Mix Type:

HL3

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	1	2	3	4	MEAN BPN	TEMP CORR BPN*	Sand Volume (mL)	Sand Patch Diameter (mm)	Mean Texture Depth (mm)	Notes
No Polishing	19	Core 1	60	58.5	58	57.5	58.5	58.2	1.7	96.5	0.23	Tested June 18, 2005
		Core 2	60	60	59	60	59.8	59.5	1.7	92.0	0.25	Tested June 18, 2005
		Core 3	56	57	57.5	58	57.1	56.9	1.7	95.8	0.23	Tested June 18, 2005
		Gyratory 1 - Bottom	68.5	69	70	70	69.4	69.1	5.0	106.75	0.56	Retested July 3
		Gyratory 1 - Top	72	72	72.5	74	72.6	72.4	5.0	114.5	0.49	Retested July 3
Low Polishing	20	Core 1	73	74	73	75	73.8	73.9				Tested Jan. 5, 2008
	19.3	Core 2	72	72	71	70	71.3	71.1				
	19.7	Core 3	70	70	70	70	70.0	70.1				
	18.4	Gyratory 1 - Bottom	70	69	70	70	69.8	69.2				
	17.6	Gyratory 1 - Top	72	72	73	74	72.8	71.9				
Medium Polishing	19.5	Core 1	65	65	63	64	64.3	64.2				
	19.6	Core 2	68	66	66	66	66.5	66.5				
	19.5	Core 3	64	64	63	63	63.5	63.5				
	17.8	Gyratory 1 - Bottom	68	69	70	69	69.0	68.2				
	18	Gyratory 1 - Top	68	67	67.5	68	67.6	66.9				
High Polishing	19.6	Core 1	60	60	58	57.5	58.9	58.9			#DIV/0!	
	19.6	Core 2	61	60	60	61	60.5	60.5			#DIV/0!	
	19.9	Core 3	60	62.5	61	61	61.1	61.3			#DIV/0!	
	18.3	Gyratory 1 - Bottom	59	60	60	59	59.5	58.9			#DIV/0!	
	18.4	Gyratory 1 - Top	62	60	60	62	61.0	60.5			#DIV/0!	

COMMENTS: *Mean BPN value is temperature corrected to 20C automatically. Individual BPN values are those recorded during the test.

Master British Pendulum and Sand Patch Test Results

Road:

SLR

Mix Type:

HL3

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	1	2	3	4	MEAN BPN	TEMP CORR BPN*	Sand Volume (mL)	Sand Patch Diameter (mm)	Mean Texture Depth (mm)	Notes
No Polishing	19	Core 1	61	59.5	60	60	60.1	59.9	1.7	82.0	0.32	Tested June 19, 2005
		Core 2	57.5	57	57	57.5	57.3	57.0	1.7	82.5	0.31	
		Core 3	61	60	60	60	60.3	60.0	1.7	88.8	0.27	
		Gyratory 1 - Bottom	59	57.5	57.5	58	58.0	57.7	5.0	118.25	0.46	
		Gyratory 1 - Top	62.5	62.5	62.5	63	62.6	62.4	5.0	117.5	0.46	
		Gyratory 2 - Bottom	64	63	63	63	63.3	63.0	5.0	118.8	0.45	
		Gyratory 2 - Top	67.5	67	65	65	66.1	65.9	5.0	119.8	0.44	
		Gyratory 3 - Top	62.5	62.5	62.5	62	62.4	62.1	5.0	113.5	0.49	
Low Polishing	19.3	Core 1	66	66	65	65	65.5	65.4				Tested Jan. 5, 2008
	19.3	Core 2	61	61	63	61	61.5	61.4				
	19.5	Core 3	66	67	67.5	68	67.1	67.1				
	20.5	Gyratory 1 - Bottom	63	62	62	62	62.3	62.7				
	20.5	Gyratory 1 - Top	64	66	64	65	64.8	65.2				
	20.8	Gyratory 2 - Bottom	62.5	62.5	62.5	63	62.6	63.2				
	20.6	Gyratory 2 - Top	67	65	65	66	65.8	66.2				
	20.5	Gyratory 3 - Top	69	69	70	68	69.0	69.4				
Medium Polishing	19	Core 1	62	60	60	61	60.8	60.5				
	18.8	Core 2	60	60	61	61	60.5	60.2				
	19.1	Core 3	67	67	65	67	66.5	66.3				
	20.2	Gyratory 1 - Bottom	67	67	66	65	66.3	66.5				
	20.1	Gyratory 1 - Top	70	70	71	70	70.3	70.5				
	20.1	Gyratory 2 - Bottom	59	60	61	60	60.0	60.2				
	20.1	Gyratory 2 - Top	69	70	70	70	69.8	70.0				

	20.1	Gyratory 3 - Top	69	70	70	69	69.5	69.7				
High Polishing	19.9	Core 1	59	60	61	60	60.0	60.2			#DIV/0!	
	19.6	Core 2	60	58	58	58	58.5	58.5			#DIV/0!	
	19.8	Core 3	58	57.5	56	58	57.4	57.5			#DIV/0!	
	20.9	Gyratory 1 - Bottom	62	62	61	62	61.8	62.4			#DIV/0!	
	20.8	Gyratory 1 - Top	60	60	60	60	60.0	60.6			#DIV/0!	
	21.1	Gyratory 2 - Bottom	62	62	62	62	62.0	62.7			#DIV/0!	
	21	Gyratory 2 - Top	62	63	64	62.5	62.9	63.5			#DIV/0!	
	21.2	Gyratory 3 - Top	63	61	61	62	61.8	62.5			#DIV/0!	

COMMENTS: *Mean BPN value is temperature corrected to 20C automatically. Individual BPN values are those recorded during the test.

Master British Pendulum and Sand Patch Test Results

Road:

DR

Mix Type:

HL3 PG 58-34 with 3% MSM

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	1	2	3	4	MEAN BPN	TEMP CORR BPN*	Sand Volume (mL)	Sand Patch Diameter (mm)	Mean Texture Depth (mm)	Notes
No Polishing	19	Core 1	70	69	69	68	69.0	68.7	1.7	92.8	0.25	Tested June 19, 2005
		Core 2	70	69.5	67.5	67.5	68.6	68.4	1.7	83.5	0.30	
		Core 3	70	70	67.5	67.5	68.8	68.5	1.7	82.5	0.31	
		Gyratory 1 - Bottom	68	67	66	66	66.8	66.5	1.7	94	0.24	
		Gyratory 1 - Top	68	67	67	67.5	67.4	67.1	5.0	142.8	0.31	
		Gyratory 2 - Bottom	68	69	68	67	68.0	67.7	1.7	99.0	0.22	
		Gyratory 2 - Top	70	70.5	67.5	69.5	69.4	69.1	5.0	141.0	0.32	
		Gyratory 3 - Bottom	68	67.5	65	65	66.4	66.1	1.7	101.8	0.21	
		Gyratory 3 - Top	72.5	72.5	73	72.5	72.6	72.4	5.0	128.8	0.38	
Low Polishing (10 cycles)	19.1	Core 1	73	70	70	69	70.5	70.3				Tested Jan. 5, 2008
	19.2	Core 2	70	69	72	72	70.8	70.6				
	19	Core 3	69	70	72	71	70.5	70.2				
	19.8	Gyratory 1 - Bottom	72	72	73	72	72.3	72.4				
	20.6	Gyratory 1 - Top	74	74	74	76	74.5	75.0				
	20.5	Gyratory 2 - Bottom	70	70	68	67.5	68.9	69.3				
	20.5	Gyratory 2 - Top	70	70	67.5	68	68.9	69.3				
	20.8	Gyratory 3 - Bottom	66	68	66	67.5	66.9	67.4				
	20.5	Gyratory 3 - Top	70	68	69	69	69.0	69.4				
Medium Polishing (30 cycles)	19.1	Core 1	62.5	62.5	64	62	62.8	62.5				
	18.8	Core 2	67	67	66	65	66.3	65.9				
	18.8	Core 3	64	65	66	65	65.0	64.7				
	20.5	Gyratory 1 - Bottom	54	55	56	54	54.8	55.2				
	20.5	Gyratory 1 - Top	62	60	61	61	61.0	61.4				

cyclics)	20.6	Gyratory 2 - Bottom	59	59	59	57.5	58.6	59.1				
	20.4	Gyratory 2 - Top	61	62	63	61	61.8	62.1				
	21.1	Gyratory 3 - Bottom	62	61	60	62	61.3	61.9				
	21	Gyratory 3 - Top	63	64	62.5	62.5	63.0	63.6				
High Polishing	19.8	Core 1	56	56	55	54	55.3	55.4				
	19.9	Core 2	62	62	62	61	61.8	61.9				
	20	Core 3	57	57.5	59	57	57.6	57.8				
	20.9	Gyratory 1 - Bottom	56	56	55	54	55.3	55.9				
	21	Gyratory 1 - Top	57	57	57	57	57.0	57.6				
	21.5	Gyratory 2 - Bottom	52	50	50	50	50.5	51.4				
	21.4	Gyratory 2 - Top	53	55	55	53	54.0	54.8				
	21.6	Gyratory 3 - Bottom	50	50	50	50	50.0	50.9				
	21.7	Gyratory 3 - Top	56	57	56	55	56.0	57.0				

COMMENTS: *Mean BPN value is temperature corrected to 20C automatically. Individual BPN values are those recorded during the test.

Master British Pendulum and Sand Patch Test Results

Road:

FR

Mix Type:

Type II Microsurfacing

Carleton

UNIVERSITY

Polish Level	Surface Temp.	Specimen	1	2	3	4	MEAN BPN	TEMP CORR BPN*	Sand Volume (mL)	Sand Patch Diameter (mm)	Mean Texture Depth (mm)	Notes
No Polishing	19	Core 1	71	70	69.5	69.5	70.0	69.7	5.0	132.0	0.37	
		Core 2	70	68	67.5	68	68.4	68.1	1.7	85.5	0.29	
		Core 3	67.5	66	64.5	65	65.8	65.5	1.7	85.5	0.29	
Low Polishing	18.4	Core 1	74	74	74	76	74.5	74.0				
	18.5	Core 2	74	72	74	72.5	73.1	72.6				
	18.7	Core 3	75	73	75	73	74.0	73.6				
Medium Polishing	19.3	Core 1	60	61	61	61	60.8	60.6				
	19.3	Core 2	65	64	65	63	64.3	64.1				
	19.2	Core 3	72	71	72	70	71.3	71.1				
High Polishing	19.6	Core 1	62	61	61	62	61.5	61.5				
	19.5	Core 2	62	62	64	62	62.5	62.5				
	19.6	Core 3	66	65	67	65	65.8	65.8				

COMMENTS:

*Mean BPN value is temperature corrected to 20C automatically. Individual BPN values are those recorded during the test.

**APPENDIX 2 – LIST OF IMAGES TAKEN WITH
MARK I PAVEMENT SURFACE IMAGER FOR
LOW TEMPERATURE INVESTIGATION**

Master Image List - Unpolished Specimens

Road: **POW**
 Mix Type: **Superpave 12.5mm FC1**

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	All Lights
-15		Core 1-1-1	Img0464	Img0465	Img0466	Img0467	Img0468
		Core 1-1-3	Img0469	Img0470	Img0471	Img0472	Img0473
		Core 1-1-4	Img0539	Img0540	Img0541	Img0542	Img0543
		Core 1-1-5	Img0474	Img0475	Img0476	Img0477	Img0478
		Core 1-1-6	Img0544	Img0545	Img0546	Img0547	Img0548
		Core 1-1-1	Img0489	Img0490	Img0491	Img0492	Img0493
-6		Core 1-1-3	Img0494	Img0495	Img0496	Img0497	Img0498
		Core 1-1-4	Img0569	Img0570	Img0571	Img0572	Img0573
		Core 1-1-5	Img0514	Img0515	Img0516	Img0517	Img0518
		Core 1-1-6	Img0584	Img0585	Img0586	Img0587	Img0588
		Core 1-1-1	Img0519	Img0520	Img0521	Img0522	Img0523
		Core 1-1-3	Img0524	Img0525	Img0526	Img0527	Img0528
0		Core 1-1-4	Img0594	Img0595	Img0596	Img0597	Img0598
		Core 1-1-5	Img0534	Img0535	Img0536	Img0537	Img0538
		Core 1-1-6	Img0614	Img0615	Img0616	Img0617	Img0618
		Core 1-1-1	Img0589	Img0590	Img0591	Img0592	Img0593
		Core 1-1-3	Img0599	Img0600	Img0601	Img0602	Img0603
		Core 1-1-4	Img0664	Img0665	Img0666	Img0667	Img0668
10		Core 1-1-5	Img0604	Img0605	Img0606	Img0607	Img0608
		Core 1-1-6	Img0669	Img0670	Img0671	Img0672	Img0673
		Core 1-1-1	Img1223	Img1224	Img1225	Img1226	Img1227
		Core 1-1-3	Img1228	Img1229	Img1230	Img1231	Img1232
		Core 1-1-4	Img1238	Img1239	Img1240	Img1241	Img1242
		Core 1-1-5	Img1233	Img1234	Img1235	Img1236	Img1237
20		Core 1-1-6	Img1243	Img1244	Img1245	Img1246	Img1247
		Gyratory 1 - Bottom	Img1113	Img1114	Img1115	Img1116	Img1117
		Gyratory 1 - Top	Img1118	Img1119	Img1120	Img1121	Img1122
		Gyratory 2 - Bottom	Img1098	Img1099	Img1100	Img1101	Img1102
		Gyratory 2 - Top	Img1093	Img1094	Img1095	Img1096	Img1097
		Gyratory 3 - Bottom	Img1068	Img1069	Img1070	Img1071	Img1072
23		Gyratory 3 - Top	Img1078	Img1079	Img1080	Img1081	Img1082

COMMENTS:

Master Image List - Unpolished Specimens

Road: **RR**
 Mix Type: **HL1 Modified**

Carleton
 UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	All Lights
No Polishing	-15	Core 1-1-1	Img0153	Img0154	Img0155	Img0156	Img0157
		Core 1-1-2	Img0218	Img0219	Img0220	Img0221	Img0222
		Core 1-1-3	Img0158	Img0159	Img0160	Img0161	Img0162
		Core 1-1-4	Img0148	Img0149	Img0150	Img0151	Img0152
		Core 1-2-1	Img0118	Img0119	Img0120	Img0121	Img0122
		Core 1-2-2	Img0223	Img0224	Img0225	Img0226	Img0227
	-6	Core 1-1-1	Img0168	Img0169	Img0170	Img0171	Img0172
		Core 1-1-2	Img0233	Img0234	Img0235	Img0236	Img0237
		Core 1-1-3	Img0178	Img0179	Img0180	Img0181	Img0182
		Core 1-1-4	Img0163	Img0164	Img0165	Img0166	Img0167
		Core 1-2-1	Img0128	Img0129	Img0130	Img0131	Img0132
		Core 1-2-2	Img0238	Img0239	Img0240	Img0241	Img0242
	0	Core 1-1-1	Img0203	Img0204	Img0205	Img0206	Img0207
		Core 1-1-2	Img0243	Img0244	Img0245	Img0246	Img0247
		Core 1-1-3	Img0188	Img0189	Img0190	Img0191	Img0192
		Core 1-1-4	Img0173	Img0174	Img0175	Img0176	Img0177
		Core 1-2-1	Img0138	Img0139	Img0140	Img0141	Img0142
		Core 1-2-2	Img0253	Img0254	Img0255	Img0256	Img0257
	10	Core 1-1-1	Img0213	Img0214	Img0215	Img0216	Img0217
		Core 1-1-2	Img0273	Img0274	Img0275	Img0276	Img0277
		Core 1-1-3	Img0208	Img0209	Img0210	Img0211	Img0212
		Core 1-1-4	Img0198	Img0199	Img0200	Img0201	Img0202
		Core 1-2-1	Img0183	Img0184	Img0185	Img0186	Img0187
		Core 1-2-2	Img0283	Img0284	Img0285	Img0286	Img0287
	23	Core 1-1-1	Img0529	Img0530	Img0531	Img0532	Img0533
		Core 1-1-2	Img0509	Img0510	Img0511	Img0512	Img0513
		Core 1-1-3	Img0504	Img0505	Img0506	Img0507	Img0508
		Core 1-1-4	Img0549	Img0550	Img0551	Img0552	Img0553
		Core 1-2-1	Img0559	Img0560	Img0561	Img0562	Img0563
		Core 1-2-2	Img0554	Img0555	Img0556	Img0557	Img0558
		Gyratory 1 - Bottom	Img1048	Img1049	Img1050	Img1051	Img1052
		Gyratory 1 - Top	Img1043	Img1044	Img1045	Img1046	Img1047
		Gyratory 2 - Bottom	Img1038	Img1039	Img1040	Img1041	Img1042
		Gyratory 2 - Top	Img1033	Img1034	Img1035	Img1036	Img1037
		Gyratory 3 - Bottom	Img1023	Img1024	Img1025	Img1026	Img1027
		Gyratory 3 - Top	Img1018	Img1019	Img1020	Img1021	Img1022
		Gyratory 4 - Bottom	Img1013	Img1014	Img1015	Img1016	Img1017
		Gyratory 4 - Bottom	Img1008	Img1009	Img1010	Img1011	Img1012
		Gyratory 5 - Top	Img1003	Img1004	Img1005	Img1006	Img1007
		Gyratory 5 - Bottom	Img0998	Img0999	Img1000	Img1001	Img1002
		Gyratory 6 - Top	Img0993	Img0994	Img0995	Img0996	Img0997
		Gyratory 6 - Bottom	Img0988	Img0989	Img0990	Img0991	Img0992
		Gyratory 7 - Top	Img0968	Img0969	Img0970	Img0971	Img0972
		Gyratory 7 - Bottom	Img0973	Img0974	Img0975	Img0976	Img0977

COMMENTS:

Master Image List - Unpolished Specimens

Road: UDHS

Mix Type: Superpave 12.5

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	All Lights
No Polishing	-15	Core 1	Img0364	Img0365	Img0366	Img0367	Img0368
		Core 2	Img0319	Img0320	Img0321	Img0322	Img0323
		Core 3	Img0314	Img0315	Img0316	Img0317	Img0318
		Core 4	Img0309	Img0310	Img0311	Img0312	Img0313
	-6	Core 1	Img0379	Img0380	Img0381	Img0382	Img0383
		Core 2	Img0339	Img0340	Img0341	Img0342	Img0343
		Core 3	Img0334	Img0335	Img0336	Img0337	Img0338
		Core 4	Img0324	Img0325	Img0326	Img0327	Img0328
	0	Core 1	Img0399	Img0400	Img0401	Img0402	Img0403
		Core 2	Img0359	Img0360	Img0361	Img0362	Img0363
		Core 3	Img0354	Img0355	Img0356	Img0357	Img0358
		Core 4	Img0344	Img0345	Img0346	Img0347	Img0348
	10	Core 1	Img0439	Img0440	Img0441	Img0442	Img0443
		Core 2	Img0429	Img0430	Img0431	Img0432	Img0433
		Core 3	Img0409	Img0410	Img0411	Img0412	Img0413
		Core 4	Img0404	Img0405	Img0406	Img0407	Img0408
	23	Core 1	Img0659	Img0660	Img0661	Img0662	Img0663
		Core 2	Img0654	Img0655	Img0656	Img0657	Img0658
		Core 3	Img0649	Img0650	Img0651	Img0652	Img0653
		Core 4	Img0644	Img0645	Img0646	Img0647	Img0648
		Gyratory 1 - Bottom	Img0953	Img0954	Img0955	Img0956	Img0957
		Gyratory 1 - Top	Img0948	Img0949	Img0950	Img0951	Img0952
		Gyratory 2 - Bottom	Img0938	Img0939	Img0940	Img0941	Img0942
		Gyratory 2 - Top	Img0933	Img0934	Img0935	Img0936	Img0937
		Gyratory 3 - Bottom	Img0928	Img0929	Img0930	Img0931	Img0932
		Gyratory 3 - Top	Img0923	Img0924	Img0925	Img0926	Img0927

COMMENTS:

Master Image List - Unpolished Specimens

Road: **UDH3**

Mix Type: **HL3**

Carleton

UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	All Lights
No Polishing	-15	Core 1	Img1058	Img1059	Img1060	Img1061	Img1062
		Core 2	Img1063	Img1064	Img1065	Img1066	Img1067
		Core 3	Img1073	Img1074	Img1075	Img1076	Img1077
	-6	Core 1	Img1083	Img1084	Img1085	Img1086	Img1087
		Core 2	Img1088	Img1089	Img1090	Img1091	Img1092
		Core 3	Img1103	Img1104	Img1105	Img1106	Img1107
	0	Core 1	Img1108	Img1109	Img1110	Img1111	Img1112
		Core 2	Img1123	Img1124	Img1125	Img1126	Img1127
		Core 3	Img1138	Img1139	Img1140	Img1141	Img1142
	10	Core 1	Img1193	Img1194	Img1195	Img1196	Img1197
		Core 2	Img1198	Img1199	Img1200	Img1201	Img1202
		Core 3	Img1203	Img1204	Img1205	Img1206	Img1207
	20	Core 1	Img1288	Img1289	Img1290	Img1291	Img1292
		Core 2	Img1283	Img1284	Img1285	Img1286	Img1287
		Core 3	Img1278	Img1279	Img1280	Img1281	Img1282

COMMENTS:

Master Image List - Unpolished Specimens

Road: **H174**
 Mix Type: **12.5mm SMA**

Carleton
 UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	All Lights
No Polishing	-16	Core 1-2-1	Img0913	Img0914	Img0915	Img0916	Img0917
		Core 1-2-3	Img0738	Img0739	Img0740	Img0741	Img0742
		Core 1-2-4	Img0768	Img0769	Img0770	Img0771	Img0772
		Core 1-3-1	Img0843	Img0844	Img0845	Img0846	Img0847
		Core 1-3-2	Img0748	Img0749	Img0750	Img0751	Img0752
		Core 1-3-3	Img0918	Img0919	Img0920	Img0921	Img0922
	-6	Core 1-2-1	Img0943	Img0944	Img0945	Img0946	Img0947
		Core 1-2-3	Img0758	Img0759	Img0760	Img0761	Img0762
		Core 1-2-4	Img0788	Img0789	Img0790	Img0791	Img0792
		Core 1-3-1	Img0883	Img0884	Img0885	Img0886	Img0887
		Core 1-3-2	Img0778	Img0779	Img0780	Img0781	Img0782
		Core 1-3-3	Img0958	Img0959	Img0960	Img0961	Img0962
	0	Core 1-2-1	Img0963	Img0964	Img0965	Img0966	Img0967
		Core 1-2-3	Img0773	Img0774	Img0775	Img0776	Img0777
		Core 1-2-4	Img0818	Img0819	Img0820	Img0821	Img0822
		Core 1-3-1	Img0908	Img0909	Img0910	Img0911	Img0912
		Core 1-3-2	Img0793	Img0794	Img0795	Img0796	Img0797
		Core 1-3-3	Img0978	Img0979	Img0980	Img0981	Img0982
	10	Core 1-2-1	Img1028	Img1029	Img1030	Img1031	Img1032
		Core 1-2-3	Img0823	Img0824	Img0825	Img0826	Img0827
		Core 1-2-4	Img0893	Img0894	Img0895	Img0896	Img0897
		Core 1-3-1	Img0983	Img0984	Img0985	Img0986	Img0987
		Core 1-3-2	Img0873	Img0874	Img0875	Img0876	Img0877
		Core 1-3-3	Img1053	Img1054	Img1055	Img1056	Img1057
	20	Core 1-2-1	Img1273	Img1274	Img1275	Img1276	Img1277
		Core 1-2-3	Img1268	Img1269	Img1270	Img1271	Img1272
		Core 1-2-4	Img1258	Img1259	Img1260	Img1261	Img1262
		Core 1-3-1	Img1248	Img1249	Img1250	Img1251	Img1252
		Core 1-3-2	Img1263	Img1264	Img1265	Img1266	Img1267
		Core 1-3-3	Img1253	Img1254	Img1255	Img1256	Img1257
	23	Gyratory 1 - Bottom	Img1188	Img1189	Img1190	Img1191	Img1192
		Gyratory 1 - Top	Img1183	Img1184	Img1185	Img1186	Img1187
		Gyratory 2 - Bottom	Img1178	Img1179	Img1180	Img1181	Img1182
		Gyratory 2 - Top	Img1173	Img1174	Img1175	Img1176	Img1177
		Gyratory 3 - Bottom	Img1168	Img1169	Img1170	Img1171	Img1172
		Gyratory 3 - Top	Img1163	Img1164	Img1165	Img1166	Img1167
		Gyratory 4 - Bottom	Img1158	Img1159	Img1160	Img1161	Img1162
		Gyratory 4 - Top	Img1153	Img1154	Img1155	Img1156	Img1157
		Gyratory 5 - Bottom	Img1148	Img1149	Img1150	Img1151	Img1152
		Gyratory 5 - Top	Img1143	Img1144	Img1145	Img1146	Img1147
		Gyratory 6 - Bottom	Img1133	Img1134	Img1135	Img1136	Img1137
		Gyratory 6 - Top	Img1128	Img1129	Img1130	Img1131	Img1132

COMMENTS:

Master Image List - Unpolished Specimens

Road:

FD

Mix Type:

HL3

Carleton

UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	All Lights
No Polishing	-15	Core 1	Img0012	Img0013	Img0014	Img0015	Img0016
		Core 2	Img0022	Img0023	Img0024	Img0025	Img0026
		Core 3	Img0047	Img0048	Img0049	Img0050	Img0051
	-6	Core 1	Img0027	Img0028	Img0029	Img0030	Img0031
		Core 2	Img0032	Img0033	Img0034	Img0035	Img0036
		Core 3	Img0057	Img0058	Img0059	Img0060	Img0061
	0	Core 1	Img0037	Img0038	Img0039	Img0040	Img0041
		Core 2	Img0042	Img0043	Img0044	Img0045	Img0046
		Core 3	Img0068	Img0069	Img0070	Img0071	Img0072
	10	Core 1	Img0073	Img0074	Img0075	Img0076	Img0077
		Core 2	Img0078	Img0079	Img0080	Img0081	Img0082
		Core 3	Img0098	Img0099	Img0100	Img0101	Img0102
	23	Core 1	Img0629	Img0630	Img0631	Img0632	Img0633
		Core 2	Img0634	Img0635	Img0636	Img0637	Img0638
		Core 3	Img0639	Img0640	Img0641	Img0642	Img0643
		Gyratory 1 - Bottom	Img0903	Img0904	Img0905	Img0906	Img0907
		Gyratory 1 - Top	Img0898	Img0899	Img0900	Img0901	Img0902
		Gyratory 2 - Bottom	Img0888	Img0889	Img0890	Img0891	Img0892
		Gyratory 2 - Top	Img0878	Img0879	Img0880	Img0881	Img0882
		Gyratory 3 - Bottom	Img0868	Img0869	Img0870	Img0871	Img0872
		Gyratory 3 - Top	Img0863	Img0864	Img0865	Img0866	Img0867

COMMENTS:

Master Image List - Unpolished Specimens

Road:

OCR

Mix Type:

HL3

Carleton

UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	All Lights
No Polishing	-15	Core 1	Img0228	Img0229	Img0230	Img0231	Img0232
		Core 2	Img0263	Img0264	Img0265	Img0266	Img0267
		Core 3	Img0268	Img0269	Img0270	Img0271	Img0272
	-6	Core 1	Img0248	Img0249	Img0250	Img0251	Img0252
		Core 2	Img0278	Img0279	Img0280	Img0281	Img0282
		Core 3	Img0288	Img0289	Img0290	Img0291	Img0292
	0	Core 1	Img0258	Img0259	Img0260	Img0261	Img0262
		Core 2	Img0293	Img0294	Img0295	Img0296	Img0297
		Core 3	Img0304	Img0305	Img0306	Img0307	Img0308
	10	Core 1	Img0298	Img0299	Img0300	Img0301	Img0303
		Core 2	Img0329	Img0330	Img0331	Img0332	Img0333
		Core 3	Img0349	Img0350	Img0351	Img0352	Img0353
	23	Core 1	Img0564	Img0565	Img0566	Img0567	Img0568
		Core 2	Img0574	Img0575	Img0576	Img0577	Img0578
		Core 3	Img0579	Img0580	Img0581	Img0582	Img0583
		Gyratory 1 - Bottom	Img0848	Img0849	Img0850	Img0851	Img0852
		Gyratory 1 - Top	Img0858	Img0859	Img0860	Img0861	Img0862
		Gyratory 3 - Bottom	Img0853	Img0854	Img0855	Img0856	Img0857

COMMENTS:

Master Image List - Unpolished Specimens

Road:

SLR

Mix Type:

HL3

Carleton

UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	All Lights
No Polishing	-15	Core 1	Img0674	Img0675	Img0676	Img0677	Img0678
		Core 2	Img0693	Img0694	Img0695	Img0696	Img0697
		Core 3	Img0708	Img0709	Img0710	Img0711	Img0712
	-6	Core 1	Img0703	Img0704	Img0705	Img0706	Img0707
		Core 2	Img0733	Img0734	Img0735	Img0736	Img0737
		Core 3	Img0743	Img0744	Img0745	Img0746	Img0747
	0	Core 1	Img0728	Img0729	Img0730	Img0731	Img0732
		Core 2	Img0753	Img0754	Img0755	Img0756	Img0757
		Core 3	Img0763	Img0764	Img0765	Img0766	Img0767
	10	Core 1	Img0783	Img0784	Img0785	Img0786	Img0787
		Core 2	Img0813	Img0814	Img0815	Img0816	Img0817
		Core 3	Img0838	Img0839	Img0840	Img0841	Img0842
	20	Core 1	Img1208	Img1209	Img1210	Img1211	Img1212
		Core 2	Img1213	Img1214	Img1215	Img1216	Img1217
		Core 3	Img1218	Img1219	Img1220	Img1221	Img1222
	23	Gyratory 1 - Bottom	Img0833	Img0834	Img0835	Img0836	Img0837
		Gyratory 1 - Top	Img0828	Img0829	Img0830	Img0831	Img0832
		Gyratory 2 - Bottom	Img0808	Img0809	Img0810	Img0811	Img0812
		Gyratory 2 - Top	Img0803	Img0804	Img0805	Img0806	Img0807
		Gyratory 3 - Top	Img0798	Img0799	Img0800	Img0801	Img0802

COMMENTS:

Master Image List - Unpolished Specimens

Road:

DR

Mix Type:

HL3

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	All Lights
No Polishing	-15	Core 1	Img0052	Img0053	Img0054	Img0055	Img0056
		Core 2	Img0088	Img0089	Img0090	Img0091	Img0092
		Core 3	Img0108	Img0109	Img0110	Img0111	Img0112
	-6	Core 1	Img0062	Img0063	Img0064	Img0065	Img0066
		Core 2	Img0093	Img0094	Img0095	Img0096	Img0097
		Core 3	Img0123	Img0124	Img0125	Img0126	Img0127
	0	Core 1	Img0083	Img0084	Img0085	Img0086	Img0087
		Core 2	Img0103	Img0104	Img0105	Img0106	Img0107
		Core 3	Img0133	Img0134	Img0135	Img0136	Img0137
	10	Core 1	Img0113	Img0114	Img0115	Img0116	Img0117
		Core 2	Img0143	Img0144	Img0145	Img0146	Img0147
		Core 3	Img0193	Img0194	Img0195	Img0196	Img0197
	23	Core 1	Img0609	Img0610	Img0611	Img0612	Img0613
		Core 2	Img0619	Img0620	Img0621	Img0622	Img0623
		Core 3	Img0624	Img0625	Img0626	Img0627	Img0628
		Gyratory 1 - Bottom	Img0723	Img0724	Img0725	Img0726	Img0727
		Gyratory 1 - Top	Img0718	Img0719	Img0720	Img0721	Img0722
		Gyratory 2 - Bottom	Img0713	Img0714	Img0715	Img0716	Img0717
		Gyratory 2 - Top	Img0698	Img0699	Img0700	Img0701	Img0702
		Gyratory 3 - Bottom	Img0684	Img0685	Img0686	Img0691	Img0692
		Gyratory 3 - Top	Img0679	Img0680	Img0681	Img0682	Img0683

COMMENTS: Image Img0626 corrupted and must be retaken.

Master Image List - Unpolished Specimens

Road: **FR**

Mix Type: **Microsurfacing Type II**

Carleton

UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	All Lights
No Polishing	-15	Core 1	Img0369	Img0370	Img0371	Img0372	Img0373
		Core 2	Img0374	Img0375	Img0376	Img0377	Img0378
		Core 3	Img0384	Img0385	Img0386	Img0387	Img0388
	-6	Core 1	Img0389	Img0390	Img0391	Img0392	Img0393
		Core 2	Img0394	Img0395	Img0396	Img0397	Img0398
		Core 3	Img0414	Img0415	Img0416	Img0417	Img0418
	0	Core 1	Img0434	Img0435	Img0436	Img0437	Img0438
		Core 2	Img0424	Img0425	Img0426	Img0427	Img0428
		Core 3	Img0419	Img0420	Img0421	Img0422	Img0423
	10	Core 1	Img0454	Img0455	Img0456	Img0457	Img0458
		Core 2	Img0444	Img0445	Img0446	Img0447	Img0448
		Core 3	Img0449	Img0450	Img0451	Img0452	Img0453
	23	Core 1	Img0499	Img0500	Img0501	Img0502	Img0503
		Core 2	Img0484	Img0485	Img0486	Img0487	Img0488
		Core 3	Img0479	Img0480	Img0481	Img0482	Img0483

COMMENTS:

**APPENDIX 3 – LIST OF IMAGES TAKEN WITH
MARK II PAVEMENT SURFACE IMAGER FOR
POLISHING INVESTIGATION**

Master Image List - Unpolished Specimens

Road: **POW**
 Mix Type: **Superpave 12.5mm FC1**
 Date:

Carleton
 UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
None	20	Core 1-1-1	UNP0861	UNP0862	UNP0863	UNP0864	UNP0865	UNP0866	UNP0867	UNP0868	UNP0869	UNP0870
		Core 1-1-3	UNP0871	UNP0872	UNP0873	UNP0874	UNP0875	UNP0876	UNP0877	UNP0878	UNP0879	UNP0880
		Core 1-1-4	UNP0881	UNP0882	UNP0883	UNP0884	UNP0885	UNP0886	UNP0887	UNP0888	UNP0889	UNP0890
		Core 1-1-5	UNP0891	UNP0892	UNP0893	UNP0894	UNP0895	UNP0896	UNP0897	UNP0898	UNP0899	UNP0900
		Core 1-1-6	UNP0901	UNP0902	UNP0903	UNP0904	UNP0905	UNP0906	UNP0907	UNP0908	UNP0909	UNP0910
		Gyratory 1 - Bottom	UNP2021	UNP2022	UNP2023	UNP2024	UNP2025	UNP2026	UNP2027	UNP2028	UNP2029	UNP2030
		Gyratory 1 - Top	UNP0921	UNP0922	UNP0923	UNP0924	UNP0925	UNP0926	UNP0927	UNP0928	UNP0929	UNP0930
		Gyratory 2 - Bottom	UNP0931	UNP0932	UNP0933	UNP0934	UNP0935	UNP0936	UNP0937	UNP0938	UNP0939	UNP0940
		Gyratory 2 - Top	UNP0941	UNP0942	UNP0943	UNP0945	UNP0946	UNP0947	UNP0948	UNP0949	UNP0950	UNP0951
		Gyratory 3 - Bottom	UNP0952	UNP0953	UNP0954	UNP0955	UNP0956	UNP0957	UNP0958	UNP0959	UNP0960	UNP0961
		Gyratory 3 - Top	UNP0962	UNP0963	UNP0964	UNP0965	UNP0966	UNP0967	UNP0968	UNP0969	UNP0970	UNP0971

COMMENTS: Images 943 and 944 are the same

Master Image List - Unpolished Specimens

Road: **RR**

Mix Type: **HL1 Modified**

Date: _____

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
None	20	Core 1-1-1	UNP0661	UNP0662	UNP0663	UNP0664	UNP0665	UNP0666	UNP0667	UNP0668	UNP0669	UNP0670
		Core 1-1-2	UNP0671	UNP0672	UNP0673	UNP0674	UNP0675	UNP0676	UNP0677	UNP0678	UNP0679	UNP0680
		Core 1-1-3	UNP0681	UNP0682	UNP0683	UNP0684	UNP0685	UNP0686	UNP0687	UNP0688	UNP0689	UNP0690
		Core 1-1-4	UNP0691	UNP0692	UNP0693	UNP0694	UNP0695	UNP0696	UNP0697	UNP0698	UNP0699	UNP0700
		Core 1-2-1	UNP0701	UNP0702	UNP0703	UNP0704	UNP0705	UNP0706	UNP0707	UNP0708	UNP0709	UNP0710
		Core 1-2-2	UNP0711	UNP0712	UNP0713	UNP0714	UNP0715	UNP0716	UNP0717	UNP0718	UNP0719	UNP0720
		Gyratory 1 - Bottom	UNP0721	UNP0722	UNP0723	UNP0724	UNP0725	UNP0726	UNP0727	UNP0728	UNP0729	UNP0730
		Gyratory 1 - Top	UNP0731	UNP0732	UNP0733	UNP0734	UNP0735	UNP0736	UNP0737	UNP0738	UNP0739	UNP0740
		Gyratory 2 - Bottom	UNP0741	UNP0742	UNP0743	UNP0744	UNP0745	UNP0746	UNP0747	UNP0748	UNP0749	UNP0750
		Gyratory 2 - Top	UNP0751	UNP0752	UNP0753	UNP0754	UNP0755	UNP0756	UNP0757	UNP0758	UNP0759	UNP0760
		Gyratory 3 - Bottom	UNP0761	UNP0762	UNP0763	UNP0764	UNP0765	UNP0766	UNP0767	UNP0768	UNP0769	UNP0770
		Gyratory 3 - Top	UNP0771	UNP0772	UNP0773	UNP0774	UNP0775	UNP0776	UNP0777	UNP0778	UNP0779	UNP0780
		Gyratory 4 - Bottom	UNP0781	UNP0782	UNP0783	UNP0784	UNP0785	UNP0786	UNP0787	UNP0788	UNP0789	UNP0790
		Gyratory 4 - Top	UNP0791	UNP0792	UNP0793	UNP0794	UNP0795	UNP0796	UNP0797	UNP0798	UNP0799	UNP0800
		Gyratory 5 - Bottom	UNP2000	UNP2001	UNP2002	UNP2003	UNP2004	UNP2005	UNP2006	UNP2007	UNP2008	UNP2009
		Gyratory 5 - Top	UNP0811	UNP0812	UNP0813	UNP0814	UNP0815	UNP0816	UNP0817	UNP0818	UNP0819	UNP0820
		Gyratory 6 - Bottom	UNP0821	UNP0822	UNP0823	UNP0824	UNP0825	UNP0826	UNP0827	UNP0828	UNP0829	UNP0830
		Gyratory 6 - Top	UNP0831	UNP0832	UNP0833	UNP0834	UNP0835	UNP0836	UNP0837	UNP0838	UNP0839	UNP0840
		Gyratory 7 - Bottom	UNP2011	UNP2012	UNP2013	UNP2014	UNP2015	UNP2016	UNP2017	UNP2018	UNP2019	UNP2020
		Gyratory 7 - Top	UNP0851	UNP0852	UNP0853	UNP0854	UNP0855	UNP0856	UNP0857	UNP0858	UNP0859	UNP0860

COMMENTS:

Master Image List - Unpolished Specimens

Road:

UDHS

Mix Type:

Superpave 12.5

Date:

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
None	23	Core 1	UNP2041	UNP2042	UNP2043	UNP2044	UNP2045	UNP2046	UNP2047	UNP2048	UNP2049	UNP2050
		Core 2	UNP0571	UNP0572	UNP0573	UNP0574	UNP0575	UNP0576	UNP0577	UNP0578	UNP0579	UNP0580
		Core 3	UNP0581	UNP0582	UNP0583	UNP0584	UNP0585	UNP0586	UNP0587	UNP0588	UNP0589	UNP0590
		Core 4	UNP0591	UNP0592	UNP0593	UNP0594	UNP0595	UNP0596	UNP0597	UNP0598	UNP0599	UNP0600
		Gyratory 1 - Bottom	UNP0601	UNP0602	UNP0603	UNP0604	UNP0605	UNP0606	UNP0607	UNP0608	UNP0609	UNP0610
		Gyratory 1 - Top	UNP0611	UNP0612	UNP0613	UNP0614	UNP0615	UNP0616	UNP0617	UNP0618	UNP0619	UNP0620
		Gyratory 2 - Bottom	UNP0621	UNP0622	UNP0623	UNP0624	UNP0625	UNP0626	UNP0627	UNP0628	UNP0629	UNP0630
		Gyratory 2 - Top	UNP0631	UNP0632	UNP0633	UNP0634	UNP0635	UNP0636	UNP0637	UNP0638	UNP0639	UNP0640
		Gyratory 3 - Bottom	UNP0641	UNP0642	UNP0643	UNP0644	UNP0645	UNP0646	UNP0647	UNP0648	UNP0649	UNP0650
		Gyratory 3 - Top	UNP2051	UNP2052	UNP2053	UNP2054	UNP2055	UNP2056	UNP2057	UNP2058	UNP2059	UNP2060

COMMENTS:

Master Image List - Unpolished Specimens

Road: UDH3

Mix Type: HL3

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
None	20	Core 1	UNP0351	UNP0352	UNP0353	UNP0354	UNP0355	UNP0356	UNP0357	UNP0358	UNP0359	UNP0360
		Core 2	UNP0361	UNP0362	UNP0363	UNP0364	UNP0365	UNP0366	UNP0367	UNP0368	UNP0369	UNP0370
		Core 3	UNP0371	UNP0372	UNP0373	UNP0374	UNP0375	UNP0376	UNP0377	UNP0378	UNP0379	UNP0380

COMMENTS:

Master Image List - Unpolished Specimens

Road: H174

Mix Type: 12.5mm SMA

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
None	20	Core 1-2-1	UNP0381	UNP0382	UNP0383	UNP0384	UNP0385	UNP0386	UNP0387	UNP0388	UNP0389	UNP0390
		Core 1-2-3	UNP0391	UNP0392	UNP0393	UNP0394	UNP0395	UNP0396	UNP0397	UNP0398	UNP0399	UNP0400
		Core 1-2-4	UNP0401	UNP0402	UNP0403	UNP0404	UNP0405	UNP0406	UNP0407	UNP0408	UNP0409	UNP0410
		Core 1-3-1	UNP0411	UNP0412	UNP0413	UNP0414	UNP0415	UNP0416	UNP0417	UNP0418	UNP0419	UNP0420
		Core 1-3-2	UNP0421	UNP0422	UNP0423	UNP0424	UNP0425	UNP0426	UNP0427	UNP0428	UNP0429	UNP0430
		Core 1-3-3	UNP0431	UNP0432	UNP0433	UNP0434	UNP0435	UNP0436	UNP0437	UNP0438	UNP0439	UNP0440
		Gyratory 1 - Bottom	UNP0441	UNP0442	UNP0443	UNP0444	UNP0445	UNP0446	UNP0447	UNP0448	UNP0449	UNP0450
		Gyratory 1 - Top	UNP0451	UNP0452	UNP0453	UNP0454	UNP0455	UNP0456	UNP0457	UNP0458	UNP0459	UNP0460
		Gyratory 2 - Bottom	UNP0461	UNP0462	UNP0463	UNP0464	UNP0465	UNP0466	UNP0467	UNP0468	UNP0469	UNP0470
		Gyratory 2 - Top	UNP0471	UNP0472	UNP0473	UNP0474	UNP0475	UNP0476	UNP0477	UNP0478	UNP0479	UNP0480
		Gyratory 3 - Bottom	UNP2031	UNP2032	UNP2033	UNP2034	UNP2035	UNP2036	UNP2037	UNP2038	UNP2039	UNP2040
		Gyratory 3 - Top	UNP0491	UNP0492	UNP0493	UNP0494	UNP0495	UNP0496	UNP0497	UNP0498	UNP0499	UNP0500
		Gyratory 4 - Bottom	UNP0501	UNP0502	UNP0503	UNP0504	UNP0505	UNP0506	UNP0507	UNP0508	UNP0509	UNP0510
		Gyratory 4 - Top	UNP0511	UNP0512	UNP0513	UNP0514	UNP0515	UNP0516	UNP0517	UNP0518	UNP0519	UNP0520
		Gyratory 5 - Bottom	UNP0521	UNP0522	UNP0523	UNP0524	UNP0525	UNP0526	UNP0527	UNP0528	UNP0529	UNP0530
		Gyratory 5 - Top	UNP0531	UNP0532	UNP0533	UNP0534	UNP0535	UNP0536	UNP0537	UNP0538	UNP0539	UNP0540
		Gyratory 6 - Bottom	UNP0541	UNP0542	UNP0543	UNP0544	UNP0545	UNP0546	UNP0547	UNP0548	UNP0549	UNP0550
		Gyratory 6 - Top	UNP0551	UNP0552	UNP0553	UNP0554	UNP0555	UNP0556	UNP0557	UNP0558	UNP0559	UNP0560

COMMENTS:

Master Image List - Unpolished Specimens

Road: **FD**

Mix Type: **HL3**

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
None	23	Core 1	UNP0201	UNP0202	UNP0203	UNP0204	UNP0205	UNP0206	UNP0207	UNP0208	UNP0209	UNP0210
		Core 2	UNP0211	UNP0212	UNP0213	UNP0214	UNP0215	UNP0216	UNP0217	UNP0218	UNP0219	UNP0220
		Core 3	UNP0221	UNP0222	UNP0223	UNP0224	UNP0225	UNP0226	UNP0227	UNP0228	UNP0229	UNP0230
		Gyratory 1 - Bottom	UNP0231	UNP0232	UNP0233	UNP0234	UNP0235	UNP0236	UNP0237	UNP0238	UNP0239	UNP0240
		Gyratory 1 - Top	UNP2161	UNP2162	UNP2163	UNP2164	UNP2165	UNP2166	UNP2167	UNP2168	UNP2169	UNP2170
		Gyratory 2 - Bottom	UNP0251	UNP0252	UNP0253	UNP0254	UNP0255	UNP0256	UNP0257	UNP0258	UNP0259	UNP0260
		Gyratory 2 - Top	UNP0261	UNP0262	UNP0263	UNP0264	UNP0265	UNP0266	UNP0267	UNP0268	UNP0269	UNP0270
		Gyratory 3 - Bottom	UNP2111	UNP2112	UNP2113	UNP2114	UNP2115	UNP2116	UNP2117	UNP2118	UNP2119	UNP2120
		Gyratory 3 - Top	UNP2121	UNP2122	UNP2123	UNP2124	UNP2125	UNP2126	UNP2127	UNP2128	UNP2129	UNP2130

COMMENTS:

Master Image List - Unpolished Specimens

Road: OCR

Mix Type: HL3

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
None	23	Core 1	UNP2061	UNP2062	UNP2063	UNP2064	UNP2065	UNP2066	UNP2067	UNP2068	UNP2069	UNP2070
		Core 2	UNP0301	UNP0302	UNP0303	UNP0304	UNP0305	UNP0306	UNP0307	UNP0308	UNP0309	UNP0310
		Core 3	UNP0311	UNP0312	UNP0313	UNP0314	UNP0315	UNP0316	UNP0317	UNP0318	UNP0319	UNP0320
		Gyratory 1 - Bottom	UNP0321	UNP0322	UNP0323	UNP0324	UNP0325	UNP0326	UNP0327	UNP0328	UNP0329	UNP0330
		Gyratory 1 - Top	UNP2071	UNP2072	UNP2073	UNP2074	UNP2075	UNP2076	UNP2077	UNP2078	UNP2079	UNP2080

COMMENTS: Gyratory 3 (Bottom) specimen has paper in Field of View

Master Image List - Unpolished Specimens

Road: SLR

Mix Type: HL3

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
None	20	Core 1	UNP0141	UNP0142	UNP0143	UNP0144	UNP0145	UNP0146	UNP0147	UNP0148	UNP0149	UNP0150
		Core 2	UNP0151	UNP0152	UNP0153	UNP0154	UNP0155	UNP0156	UNP0157	UNP0158	UNP0159	UNP0160
		Core 3	UNP0161	UNP0162	UNP0163	UNP0164	UNP0165	UNP0166	UNP0167	UNP0168	UNP0169	UNP0170
		Gyratory 1 - Bottom	UNP0091	UNP0092	UNP0093	UNP0094	UNP0095	UNP0096	UNP0097	UNP0098	UNP0099	UNP0100
		Gyratory 1 - Top	UNP0101	UNP0102	UNP0103	UNP0104	UNP0105	UNP0106	UNP0107	UNP0108	UNP0109	UNP0110
		Gyratory 2 - Bottom	UNP0111	UNP0112	UNP0113	UNP0114	UNP0115	UNP0116	UNP0117	UNP0118	UNP0119	UNP0120
		Gyratory 2 - Top	UNP0121	UNP0122	UNP0123	UNP0124	UNP0125	UNP0126	UNP0127	UNP0128	UNP0129	UNP0130
		Gyratory 3 - Top	UNP2131	UNP2132	UNP2133	UNP2134	UNP2135	UNP2136	UNP2137	UNP2138	UNP2139	UNP2140

COMMENTS:

Master Image List - Unpolished Specimens

Road: DR

Mix Type: HL3

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
None	20	Core 1	UNP0061	UNP0062	UNP0063	UNP0064	UNP0065	UNP0066	UNP0067	UNP0068	UNP0069	UNP0070
		Core 2	UNP0071	UNP0072	UNP0073	UNP0074	UNP0075	UNP0076	UNP0077	UNP0078	UNP0079	UNP0080
		Core 3	UNP0081	UNP0082	UNP0083	UNP0084	UNP0085	UNP0086	UNP0087	UNP0088	UNP0089	UNP0090
		Gyratory 1 - Bottom	UNP0011	UNP0012	UNP0013	UNP0014	UNP0015	UNP0016	UNP0017	UNP0018	UNP0019	UNP0020
		Gyratory 1 - Top	UNP0001	UNP0002	UNP0003	UNP0004	UNP0005	UNP0006	UNP0007	UNP0008	UNP0009	UNP0010
		Gyratory 2 - Bottom	UNP0021	UNP0022	UNP0023	UNP0024	UNP0025	UNP0026	UNP0027	UNP0028	UNP0029	UNP0030
		Gyratory 2 - Top	UNP0031	UNP0032	UNP0033	UNP0034	UNP0035	UNP0036	UNP0037	UNP0038	UNP0039	UNP0040
		Gyratory 3 - Bottom	UNP0041	UNP0042	UNP0043	UNP0044	UNP0045	UNP0046	UNP0047	UNP0048	UNP0049	UNP0050
		Gyratory 3 - Top	UNP0051	UNP0052	UNP0053	UNP0054	UNP0055	UNP0056	UNP0057	UNP0058	UNP0059	UNP0060

COMMENTS:

Master Image List - Unpolished Specimens

Road:

FR

Mix Type: Microsurfacing Type II

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
None	20	Core 1	UNP0171	UNP0172	UNP0173	UNP0174	UNP0175	UNP0176	UNP0177	UNP0178	UNP0179	UNP0180
		Core 2	UNP0181	UNP0182	UNP0183	UNP0184	UNP0185	UNP0186	UNP0187	UNP0188	UNP0189	UNP0190
		Core 3	UNP0191	UNP0192	UNP0193	UNP0194	UNP0195	UNP0196	UNP0197	UNP0198	UNP0199	UNP0200

COMMENTS:

Master Image List - Low Specimen Polish

Road: **POW**

Mix Type: **Superpave 12.5mm FC1**

Date:

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Low (10 cycles)	20	Core 1-1-1	LOW0847	LOW0848	LOW0849	LOW0850	LOW0851	LOW0852	LOW0853	LOW0854	LOW0855	LOW0856
		Core 1-1-3	LOW0857	LOW0858	LOW0859	LOW0860	LOW0861	LOW0862	LOW0863	LOW0864	LOW0865	LOW0866
		Core 1-1-4	LOW0867	LOW0868	LOW0869	LOW0870	LOW0871	LOW0872	LOW0873	LOW0874	LOW0875	LOW0876
		Core 1-1-5	LOW0877	LOW0878	LOW0879	LOW0880	LOW0881	LOW0882	LOW0883	LOW0884	LOW0885	LOW0886
		Core 1-1-6	LOW0887	LOW0888	LOW0889	LOW0890	LOW0891	LOW0892	LOW0893	LOW0894	LOW0895	LOW0896
		Gyratory 1 - Bottom	LOW0897	LOW0898	LOW0899	LOW0900	LOW0901	LOW0902	LOW0903	LOW0904	LOW0905	LOW0906
		Gyratory 1 - Top	LOW0907	LOW0908	LOW0909	LOW0910	LOW0911	LOW0912	LOW0913	LOW0914	LOW0915	LOW0916
		Gyratory 2 - Bottom	LOW0917	LOW0918	LOW0919	LOW0920	LOW0921	LOW0922	LOW0923	LOW0924	LOW0925	LOW0926
		Gyratory 2 - Top	LOW1027	LOW1028	LOW1029	LOW1030	LOW1031	LOW1032	LOW1033	LOW1034	LOW1035	LOW1036
		Gyratory 3 - Bottom	LOW0937	LOW0938	LOW0939	LOW0940	LOW0941	LOW0942	LOW0943	LOW0944	LOW0945	LOW0946
		Gyratory 3 - Top	LOW0947	LOW0948	LOW0949	LOW0950	LOW0951	LOW0952	LOW0953	LOW0954	LOW0955	LOW0956

COMMENTS:

Master Image List - Low Specimen Polish

Carleton

UNIVERSITY

Road:

RR

Mix Type:

HL1 Modified

Date:

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Low (10 cycles)	20	Core 1-1-1	LOW0644	LOW0645	LOW0646	LOW0648	LOW0649	LOW0650	LOW0651	LOW0652	LOW0653	LOW0654
		Core 1-1-2	LOW0655	LOW0656	LOW0657	LOW0658	LOW0659	LOW0660	LOW0661	LOW0662	LOW0663	LOW0664
		Core 1-1-3	LOW0665	LOW0667	LOW0668	LOW0669	LOW0670	LOW0671	LOW0672	LOW0673	LOW0674	LOW0675
		Core 1-1-4	LOW1037	LOW1038	LOW1039	LOW1040	LOW1041	LOW1042	LOW1043	LOW1044	LOW1045	LOW1046
		Core 1-2-1	LOW0687	LOW0688	LOW0689	LOW0690	LOW0691	LOW0692	LOW0693	LOW0694	LOW0695	LOW0696
		Core 1-2-2	LOW0697	LOW0698	LOW0699	LOW0700	LOW0701	LOW0702	LOW0703	LOW0704	LOW0705	LOW0706
		Gyratory 1 - Bottom	LOW0717	LOW0718	LOW0719	LOW0720	LOW0721	LOW0722	LOW0723	LOW0724	LOW0725	LOW0726
		Gyratory 1 - Top	LOW0727	LOW0728	LOW0729	LOW0730	LOW0731	LOW0732	LOW0733	LOW0734	LOW0735	LOW0736
		Gyratory 2 - Bottom	LOW0737	LOW0738	LOW0739	LOW0740	LOW0741	LOW0742	LOW0743	LOW0744	LOW0745	LOW0746
		Gyratory 2 - Top	LOW0747	LOW0748	LOW0749	LOW0750	LOW0751	LOW0752	LOW0753	LOW0754	LOW0755	LOW0756
		Gyratory 3 - Bottom	LOW0757	LOW0758	LOW0759	LOW0760	LOW0761	LOW0762	LOW0763	LOW0764	LOW0765	LOW0766
		Gyratory 3 - Top	LOW1047	LOW1048	LOW1049	LOW1050	LOW1051	LOW1052	LOW1053	LOW1054	LOW1055	LOW1056
		Gyratory 4 - Bottom	LOW0777	LOW0778	LOW0779	LOW0780	LOW0781	LOW0782	LOW0783	LOW0784	LOW0785	LOW0786
		Gyratory 4 - Top	LOW0787	LOW0788	LOW0789	LOW0790	LOW0791	LOW0792	LOW0793	LOW0794	LOW0795	LOW0796
		Gyratory 5 - Bottom	LOW0797	LOW0798	LOW0799	LOW0800	LOW0801	LOW0802	LOW0803	LOW0804	LOW0805	LOW0806
		Gyratory 5 - Top	LOW0807	LOW0808	LOW0809	LOW0810	LOW0811	LOW0812	LOW0813	LOW0814	LOW0815	LOW0816
		Gyratory 6 - Bottom	LOW0817	LOW0818	LOW0819	LOW0820	LOW0821	LOW0822	LOW0823	LOW0824	LOW0825	LOW0826
		Gyratory 6 - Top	LOW0957	LOW0958	LOW0959	LOW0960	LOW0961	LOW0962	LOW0963	LOW0964	LOW0965	LOW0966
		Gyratory 7 - Bottom	LOW0827	LOW0828	LOW0829	LOW0830	LOW0831	LOW0832	LOW0833	LOW0834	LOW0835	LOW0836
		Gyratory 7 - Top	LOW1077	LOW1078	LOW1079	LOW1080	LOW1081	LOW1082	LOW1083	LOW1084	LOW1085	LOW1086

COMMENTS:

Delete 647, 666 and 677

Master Image List - Low Specimen Polish

Road: UDHS

Mix Type: Superpave 12.5

Date:

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Low (10 cycles)	22	Core 1	LOW0987	LOW0988	LOW0989	LOW0990	LOW0991	LOW0992	LOW0993	LOW0994	LOW0995	LOW0996
		Core 2	LOW0323	LOW0324	LOW0325	LOW0326	LOW0327	LOW0328	LOW0329	LOW0330	LOW0331	LOW0332
		Core 3	LOW0333	LOW0334	LOW0335	LOW0336	LOW0337	LOW0338	LOW0339	LOW0340	LOW0341	LOW0342
		Core 4	LOW0343	LOW0344	LOW0345	LOW0346	LOW0347	LOW0348	LOW0349	LOW0350	LOW0351	LOW0352
		Gyratory 1 - Bottom	LOW0353	LOW0354	LOW0355	LOW0356	LOW0357	LOW0358	LOW0359	LOW0360	LOW0361	LOW0362
		Gyratory 1 - Top	LOW0363	LOW0364	LOW0365	LOW0366	LOW0367	LOW0368	LOW0369	LOW0370	LOW0371	LOW0372
		Gyratory 2 - Bottom	LOW0373	LOW0374	LOW0375	LOW0376	LOW0377	LOW0378	LOW0379	LOW0380	LOW0381	LOW0382
		Gyratory 2 - Top	LOW0383	LOW0384	LOW0385	LOW0386	LOW0387	LOW0388	LOW0389	LOW0390	LOW0391	LOW0392
		Gyratory 3 - Bottom	LOW0393	LOW0394	LOW0395	LOW0396	LOW0397	LOW0398	LOW0399	LOW0400	LOW0401	LOW0402
		Gyratory 3 - Top	LOW0403	LOW0404	LOW0405	LOW0406	LOW0407	LOW0408	LOW0409	LOW0410	LOW0411	LOW0412

COMMENTS: Deleted LOW0313

Master Image List - Low Specimen Polish

Road: UDH3

Mix Type: HL3

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Low (10 cycles)	20	Core 1	LOW0413	LOW0414	LOW0415	LOW0416	LOW0417	LOW0418	LOW0419	LOW0420	LOW0421	LOW0422
		Core 2	LOW1067	LOW1068	LOW1069	LOW1070	LOW1071	LOW1072	LOW1073	LOW1074	LOW1075	LOW1076
		Core 3	LOW0433	LOW0434	LOW0435	LOW0436	LOW0437	LOW0438	LOW0439	LOW0440	LOW0441	LOW0442

COMMENTS:

Master Image List - Low Specimen Polish

Road: H174

Mix Type: 12.5mm SMA

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Low (10 cycles)	20	Core 1-2-1	LOW0474	LOW0475	LOW0476	LOW0477	LOW0478	LOW0479	LOW0480	LOW0481	LOW0482	LOW0483
		Core 1-2-3	LOW0484	LOW0485	LOW0486	LOW0487	LOW0488	LOW0489	LOW0490	LOW0491	LOW0492	LOW0493
		Core 1-2-4	LOW0494	LOW0495	LOW0496	LOW0497	LOW0498	LOW0499	LOW0500	LOW0501	LOW0502	LOW0503
		Core 1-3-1	LOW1007	LOW1008	LOW1009	LOW1010	LOW1011	LOW1012	LOW1013	LOW1014	LOW1015	LOW1016
		Core 1-3-2	LOW0514	LOW0515	LOW0516	LOW0517	LOW0518	LOW0519	LOW0520	LOW0521	LOW0522	LOW0523
		Core 1-3-3	LOW0524	LOW0525	LOW0526	LOW0527	LOW0528	LOW0529	LOW0530	LOW0531	LOW0532	LOW0533
		Gyratory 1 - Bottom	LOW0534	LOW0535	LOW0536	LOW0537	LOW0538	LOW0539	LOW0540	LOW0541	LOW0542	LOW0543
		Gyratory 1 - Top	LOW0544	LOW0545	LOW0546	LOW0547	LOW0548	LOW0549	LOW0550	LOW0551	LOW0552	LOW0553
		Gyratory 2 - Bottom	LOW0554	LOW0555	LOW0556	LOW0557	LOW0558	LOW0559	LOW0560	LOW0561	LOW0562	LOW0563
		Gyratory 2 - Top	LOW0564	LOW0565	LOW0566	LOW0567	LOW0568	LOW0569	LOW0570	LOW0571	LOW0572	LOW0573
		Gyratory 3 - Bottom	LOW1017	LOW1018	LOW1019	LOW1020	LOW1021	LOW1022	LOW1023	LOW1024	LOW1025	LOW1026
		Gyratory 3 - Top	LOW0584	LOW0585	LOW0586	LOW0587	LOW0588	LOW0589	LOW0590	LOW0591	LOW0592	LOW0593
		Gyratory 4 - Bottom	LOW0707	LOW0708	LOW0709	LOW0710	LOW0711	LOW0712	LOW0713	LOW0714	LOW0715	LOW0716
		Gyratory 4 - Top	LOW0594	LOW0595	LOW0596	LOW0597	LOW0598	LOW0599	LOW0600	LOW0601	LOW0602	LOW0603
		Gyratory 5 - Bottom	LOW0604	LOW0605	LOW0606	LOW0607	LOW0608	LOW0609	LOW0610	LOW0611	LOW0612	LOW0613
		Gyratory 5 - Top	LOW0614	LOW0615	LOW0616	LOW0617	LOW0618	LOW0619	LOW0620	LOW0621	LOW0622	LOW0623
		Gyratory 6 - Bottom	LOW0624	LOW0625	LOW0626	LOW0627	LOW0628	LOW0629	LOW0630	LOW0631	LOW0632	LOW0633
		Gyratory 6 - Top	LOW0634	LOW0635	LOW0636	LOW0637	LOW0638	LOW0639	LOW0640	LOW0641	LOW0642	LOW0643

COMMENTS:

Master Image List - Low Specimen Polish

Road: FD

Mix Type: HL3

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Low (10 cycles)	23	Core 1	LOW0282	LOW0283	LOW0284	LOW0285	LOW0286	LOW0287	LOW0288	LOW0289	LOW0290	LOW0291
		Core 2	LOW0292	LOW0293	LOW0294	LOW0295	LOW0296	LOW0297	LOW0298	LOW0299	LOW0300	LOW0301
		Core 3	LOW0302	LOW0303	LOW0304	LOW0305	LOW0306	LOW0307	LOW0308	LOW0309	LOW0310	LOW0311
		Gyratory 1 - Bottom	LOW0221	LOW0222	LOW0223	LOW0224	LOW0225	LOW0226	LOW0227	LOW0228	LOW0229	LOW0230
		Gyratory 1 - Top	LOW0231	LOW0232	LOW0233	LOW0234	LOW0235	LOW0236	LOW0237	LOW0238	LOW0239	LOW0240
		Gyratory 2 - Bottom	LOW0997	LOW0998	LOW0999	LOW1000	LOW1001	LOW1002	LOW1003	LOW1004	LOW1005	LOW1006
		Gyratory 2 - Top	LOW0251	LOW0252	LOW0253	LOW0254	LOW0255	LOW0256	LOW0257	LOW0258	LOW0259	LOW0260
		Gyratory 3 - Bottom	LOW0261	LOW0262	LOW0263	LOW0264	LOW0265	LOW0266	LOW0267	LOW0268	LOW0269	LOW0270
		Gyratory 3 - Top	LOW0271	LOW0272	LOW0273	LOW0274	LOW0275	LOW0276	LOW0277	LOW0278	LOW0279	LOW0280

COMMENTS: LOW0274 is to be deleted.

Master Image List - Low Specimen Polish

Road: **OCR**

Mix Type: **HL3**

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Low (10 cycles)	20	Core 1	LOW0191	LOW0192	LOW0193	LOW0194	LOW0195	LOW0196	LOW0197	LOW0198	LOW0199	LOW0200
		Core 2	LOW0201	LOW0202	LOW0203	LOW0204	LOW0205	LOW0206	LOW0207	LOW0208	LOW0209	LOW0210
		Core 3	LOW0211	LOW0212	LOW0213	LOW0214	LOW0215	LOW0216	LOW0217	LOW0218	LOW0219	LOW0220
		Gyratory 1 - Bottom	LOW0171	LOW0172	LOW0173	LOW0174	LOW0175	LOW0176	LOW0177	LOW0178	LOW0179	LOW0180
		Gyratory 1 - Top	LOW0181	LOW0182	LOW0183	LOW0184	LOW0185	LOW0186	LOW0187	LOW0188	LOW0189	LOW0190

COMMENTS:

Master Image List - Low Specimen Polish

Road: SLR

Mix Type: HL3

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Low (10 cycles)	20	Core 1	LOW0141	LOW0142	LOW0143	LOW0144	LOW0145	LOW0146	LOW0147	LOW0148	LOW0149	LOW0150
		Core 2	LOW0151	LOW0152	LOW0153	LOW0154	LOW0155	LOW0156	LOW0157	LOW0158	LOW0159	LOW0160
		Core 3	LOW0161	LOW0162	LOW0163	LOW0164	LOW0165	LOW0166	LOW0167	LOW0168	LOW0169	LOW0170
		Gyratory 1 - Bottom	LOW0091	LOW0092	LOW0093	LOW0094	LOW0095	LOW0096	LOW0097	LOW0098	LOW0099	LOW0100
		Gyratory 1 - Top	LOW0101	LOW0102	LOW0103	LOW0104	LOW0105	LOW0106	LOW0107	LOW0108	LOW0109	LOW0110
		Gyratory 2 - Bottom	LOW0111	LOW0112	LOW0113	LOW0114	LOW0115	LOW0116	LOW0117	LOW0118	LOW0119	LOW0120
		Gyratory 2 - Top	LOW0121	LOW0122	LOW0123	LOW0124	LOW0125	LOW0126	LOW0127	LOW0128	LOW0129	LOW0130
		Gyratory 3 - Top	LOW0131	LOW0132	LOW0133	LOW0134	LOW0135	LOW0136	LOW0137	LOW0138	LOW0139	LOW0140

COMMENTS:

Master Image List - Low Specimen Polish

Road: DR

Mix Type: HL3

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Low (10 cycles)	20	Core 1	LOW0061	LOW0062	LOW0063	LOW0064	LOW0065	LOW0066	LOW0067	LOW0068	LOW0069	LOW0070
		Core 2	LOW0071	LOW0072	LOW0073	LOW0074	LOW0075	LOW0076	LOW0077	LOW0078	LOW0079	LOW0080
		Core 3	LOW0081	LOW0082	LOW0083	LOW0084	LOW0085	LOW0086	LOW0087	LOW0088	LOW0089	LOW0090
		Gyratory 1 - Bottom	LOW0001	LOW0002	LOW0003	LOW0004	LOW0005	LOW0006	LOW0007	LOW0008	LOW0009	LOW0010
		Gyratory 1 - Top	LOW0011	LOW0012	LOW0013	LOW0014	LOW0015	LOW0016	LOW0017	LOW0018	LOW0019	LOW0020
		Gyratory 2 - Bottom	LOW0021	LOW0022	LOW0023	LOW0024	LOW0025	LOW0026	LOW0027	LOW0028	LOW0029	LOW0030
		Gyratory 2 - Top	LOW0031	LOW0032	LOW0033	LOW0034	LOW0035	LOW0036	LOW0037	LOW0038	LOW0039	LOW0040
		Gyratory 3 - Bottom	LOW0041	LOW0042	LOW0043	LOW0044	LOW0045	LOW0046	LOW0047	LOW0048	LOW0049	LOW0050
		Gyratory 3 - Top	LOW0051	LOW0052	LOW0053	LOW0054	LOW0055	LOW0056	LOW0057	LOW0058	LOW0059	LOW0060

COMMENTS:

Master Image List - Low Specimen Polish

Road: FR
Mix Type: Microsurfacing Type II

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Low (10 cycles)	20	Core 1	LOW0967	LOW0968	LOW0969	LOW0970	LOW0971	LOW0972	LOW0973	LOW0974	LOW0975	LOW0976
		Core 2	LOW0454	LOW0455	LOW0456	LOW0457	LOW0458	LOW0459	LOW0460	LOW0461	LOW0462	LOW0463
		Core 3	LOW0464	LOW0465	LOW0466	LOW0467	LOW0468	LOW0469	LOW0470	LOW0471	LOW0472	LOW0473

COMMENTS: Deleted LOW0452

Master Image List - Medium Specimen Polish

Road: **POW**
 Mix Type: **Superpave 12.5mm FC1**
 Date:

Carleton
 UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Medium (30 cycles)	20	Core 1-1-1	MED0773	MED0774	MED0775	MED0776	MED0777	MED0778	MED0779	MED0780	MED0781	MED0782
		Core 1-1-3	MED0791	MED0792	MED0793	MED0794	MED0795	MED0796	MED0797	MED0798	MED0799	MED0800
		Core 1-1-4	MED0801	MED0802	MED0803	MED0804	MED0805	MED0806	MED0807	MED0808	MED0809	MED0810
		Core 1-1-5	MED0811	MED0812	MED0813	MED0814	MED0815	MED0816	MED0817	MED0818	MED0819	MED0820
		Core 1-1-6	MED0821	MED0822	MED0823	MED0824	MED0825	MED0826	MED0827	MED0828	MED0829	MED0830
		Gyratory 1 - Bottom	MED0831	MED0832	MED0833	MED0834	MED0835	MED0836	MED0837	MED0838	MED0839	MED0840
		Gyratory 1 - Top	MED0841	MED0842	MED0843	MED0844	MED0845	MED0846	MED0847	MED0848	MED0849	MED0850
		Gyratory 2 - Bottom	MED0851	MED0852	MED0853	MED0854	MED0855	MED0856	MED0857	MED0858	MED0859	MED0860
		Gyratory 2 - Top	MED0861	MED0862	MED0863	MED0865	MED0866	MED0867	MED0868	MED0869	MED0870	MED0871
		Gyratory 3 - Bottom	MED0892	MED0893	MED0894	MED0895	MED0896	MED0897	MED0898	MED0899	MED0900	MED0901
		Gyratory 3 - Top	MED0882	MED0883	MED0884	MED0885	MED0886	MED0887	MED0888	MED0889	MED0890	MED0891

COMMENTS:

Master Image List - Medium Specimen Polish

Road:

RR

Mix Type:

HL1 Modified

Date:

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Medium (30 cycles)	20	Core 1-1-1	MED0902	MED0903	MED0904	MED0905	MED0906	MED0907	MED0908	MED0909	MED0910	MED0911
		Core 1-1-2	MED0912	MED0913	MED0914	MED0915	MED0916	MED0917	MED0918	MED0919	MED0920	MED0921
		Core 1-1-3	MED0922	MED0923	MED0924	MED0925	MED0926	MED0927	MED0928	MED0929	MED0930	MED0931
		Core 1-1-4	MED0932	MED0933	MED0934	MED0935	MED0936	MED0937	MED0938	MED0939	MED0940	MED0941
		Core 1-2-1	MED1022	MED1023	MED1024	MED1025	MED1026	MED1027	MED1028	MED1029	MED1030	MED1031
		Core 1-2-2	MED0952	MED0953	MED0954	MED0955	MED0956	MED0957	MED0958	MED0959	MED0960	MED0961
		Gyratory 1 - Bottom	MED0962	MED0963	MED0964	MED0965	MED0966	MED0967	MED0968	MED0969	MED0970	MED0971
		Gyratory 1 - Top	MED0972	MED0973	MED0974	MED0975	MED0976	MED0977	MED0978	MED0979	MED0980	MED0981
		Gyratory 2 - Bottom	MED1032	MED1033	MED1034	MED1035	MED1036	MED1037	MED1038	MED1039	MED1040	MED1041
		Gyratory 2 - Top	MED1042	MED1043	MED1044	MED1045	MED1046	MED1047	MED1048	MED1049	MED1050	MED1051
		Gyratory 3 - Bottom	MED1052	MED1053	MED1054	MED1055	MED1056	MED1057	MED1058	MED1059	MED1060	MED1061
		Gyratory 3 - Top	MED1012	MED1013	MED1014	MED1015	MED1016	MED1017	MED1018	MED1019	MED1020	MED1021
		Gyratory 4 - Bottom	MED1062	MED1063	MED1064	MED1065	MED1066	MED1067	MED1068	MED1069	MED1070	MED1071
		Gyratory 4 - Top	MED1072	MED1073	MED1074	MED1075	MED1076	MED1077	MED1078	MED1079	MED1080	MED1081
		Gyratory 5 - Bottom	MED1082	MED1083	MED1084	MED1085	MED1086	MED1087	MED1088	MED1089	MED1090	MED1091
		Gyratory 5 - Top	MED1092	MED1093	MED1094	MED1095	MED1096	MED1097	MED1098	MED1099	MED1100	MED1101
		Gyratory 6 - Bottom	MED1152	MED1153	MED1154	MED1155	MED1156	MED1157	MED1158	MED1159	MED1160	MED1161
		Gyratory 6 - Top	MED1112	MED1113	MED1114	MED1115	MED1116	MED1117	MED1118	MED1119	MED1120	MED1121
		Gyratory 7 - Bottom	MED1122	MED1123	MED1124	MED1125	MED1126	MED1127	MED1128	MED1129	MED1130	MED1131
		Gyratory 7 - Top	MED1132	MED1133	MED1134	MED1135	MED1136	MED1137	MED1138	MED1139	MED1140	MED1141

COMMENTS:

Master Image List - Medium Specimen Polish

Road: **UDHS**
 Mix Type: **Superpave 12.5**
 Date: _____

Carleton
 UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Medium (30 cycles)	22	Core 1	MED0411	MED0412	MED0413	MED0414	MED0415	MED0416	MED0417	MED0418	MED0419	MED0420
		Core 2	MED0622	MED0623	MED0624	MED0625	MED0626	MED0627	MED0628	MED0629	MED0630	MED0632
		Core 3	MED0431	MED0432	MED0433	MED0434	MED0435	MED0436	MED0437	MED0438	MED0439	MED0440
		Core 4	MED0441	MED0442	MED0443	MED0444	MED0445	MED0446	MED0447	MED0448	MED0449	MED0450
		Gyratory 1 - Bottom	MED0452	MED0453	MED0454	MED0455	MED0456	MED0457	MED0458	MED0459	MED0460	MED0461
		Gyratory 1 - Top	MED0462	MED0463	MED0464	MED0465	MED0466	MED0467	MED0468	MED0469	MED0470	MED0471
		Gyratory 2 - Bottom	MED0522	MED0523	MED0524	MED0525	MED0526	MED0527	MED0528	MED0529	MED0530	MED0531
		Gyratory 2 - Top	MED0482	MED0483	MED0484	MED0485	MED0486	MED0487	MED0488	MED0489	MED0490	MED0491
		Gyratory 3 - Bottom	MED0492	MED0493	MED0494	MED0495	MED0496	MED0497	MED0498	MED0499	MED0500	MED0501
		Gyratory 3 - Top	MED0502	MED0503	MED0504	MED0505	MED0506	MED0507	MED0508	MED0509	MED0510	MED0511

COMMENTS: Deleted MED0631

Master Image List - Medium Specimen Polish

Road: UDH3

Mix Type: HL3

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Medium (30 cycles)	20	Core 1	MED0633	MED0634	MED0635	MED0636	MED0637	MED0638	MED0639	MED0640	MED0641	MED0642
		Core 2	MED0542	MED0543	MED0544	MED0545	MED0546	MED0547	MED0548	MED0549	MED0550	MED0551
		Core 3	MED0643	MED0644	MED0645	MED0646	MED0647	MED0648	MED0649	MED0650	MED0651	MED0652

COMMENTS:

Master Image List - Medium Specimen Polish

Road: H174

Mix Type: 12.5mm SMA

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Medium (30 cycles)	20	Core 1-2-1	MED0562	MED0563	MED0564	MED0565	MED0566	MED0567	MED0568	MED0569	MED0570	MED0571
		Core 1-2-3	MED0572	MED0573	MED0574	MED0575	MED0576	MED0577	MED0578	MED0579	MED0580	MED0581
		Core 1-2-4	MED0582	MED0583	MED0584	MED0585	MED0586	MED0587	MED0588	MED0589	MED0590	MED0591
		Core 1-3-1	MED0592	MED0593	MED0594	MED0595	MED0596	MED0597	MED0598	MED0599	MED0600	MED0601
		Core 1-3-2	MED0602	MED0603	MED0604	MED0605	MED0606	MED0607	MED0608	MED0609	MED0610	MED0611
		Core 1-3-3	MED0612	MED0613	MED0614	MED0615	MED0616	MED0617	MED0618	MED0619	MED0620	MED0621
		Gyratory 1 - Bottom	MED0653	MED0654	MED0655	MED0656	MED0657	MED0658	MED0659	MED0660	MED0661	MED0662
		Gyratory 1 - Top	MED0663	MED0664	MED0665	MED0666	MED0667	MED0668	MED0669	MED0670	MED0671	MED0672
		Gyratory 2 - Bottom	MED0673	MED0674	MED0675	MED0676	MED0677	MED0678	MED0679	MED0680	MED0681	MED0682
		Gyratory 2 - Top	MED0683	MED0684	MED0685	MED0686	MED0687	MED0688	MED0689	MED0690	MED0691	MED0692
		Gyratory 3 - Bottom	MED0693	MED0694	MED0695	MED0696	MED0697	MED0698	MED0699	MED0700	MED0701	MED0702
		Gyratory 3 - Top	MED0703	MED0704	MED0705	MED0706	MED0707	MED0708	MED0709	MED0710	MED0711	MED0712
		Gyratory 4 - Bottom	MED0713	MED0714	MED0715	MED0716	MED0717	MED0718	MED0719	MED0720	MED0721	MED0722
		Gyratory 4 - Top	MED0723	MED0724	MED0725	MED0726	MED0727	MED0728	MED0729	MED0730	MED0731	MED0732
		Gyratory 5 - Bottom	MED0733	MED0734	MED0735	MED0736	MED0737	MED0738	MED0739	MED0740	MED0741	MED0742
		Gyratory 5 - Top	MED0743	MED0744	MED0745	MED0746	MED0747	MED0748	MED0749	MED0750	MED0751	MED0752
		Gyratory 6 - Bottom	MED0753	MED0754	MED0755	MED0756	MED0757	MED0758	MED0759	MED0760	MED0761	MED0762
		Gyratory 6 - Top	MED0763	MED0764	MED0765	MED0766	MED0767	MED0768	MED0769	MED0770	MED0771	MED0772

COMMENTS:

Master Image List - Medium Specimen Polish

Road: **FD**

Mix Type: **HL3**

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Medium (30 cycles)	23	Core 1	MED0401	MED0402	MED0403	MED0404	MED0405	MED0406	MED0407	MED0408	MED0409	MED0410
		Core 2	MED0301	MED0302	MED0303	MED0304	MED0305	MED0306	MED0307	MED0308	MED0309	MED0310
		Core 3	MED0311	MED0312	MED0313	MED0314	MED0315	MED0316	MED0317	MED0318	MED0319	MED0320
		Gyratory 1 - Bottom	MED0391	MED0392	MED0393	MED0394	MED0395	MED0396	MED0397	MED0398	MED0399	MED0400
		Gyratory 1 - Top	MED0331	MED0332	MED0333	MED0334	MED0335	MED0336	MED0337	MED0338	MED0339	MED0340
		Gyratory 2 - Bottom	MED0341	MED0342	MED0343	MED0344	MED0345	MED0346	MED0347	MED0348	MED0349	MED0350
		Gyratory 2 - Top	MED0351	MED0352	MED0353	MED0354	MED0355	MED0356	MED0357	MED0358	MED0359	MED0360
		Gyratory 3 - Bottom	MED0361	MED0362	MED0363	MED0364	MED0365	MED0366	MED0367	MED0368	MED0369	MED0370
		Gyratory 3 - Top	MED0381	MED0382	MED0383	MED0384	MED0385	MED0386	MED0387	MED0388	MED0389	MED0390

COMMENTS:

Master Image List - Medium Specimen Polish

Road: OCR

Mix Type: HL3

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Medium (30 cycles)	20	Core 1	MED0221	MED0222	MED0223	MED0224	MED0225	MED0226	MED0227	MED0228	MED0229	MED0230
		Core 2	MED0231	MED0232	MED0233	MED0234	MED0235	MED0236	MED0237	MED0238	MED0239	MED0240
		Core 3	MED0261	MED0262	MED0263	MED0264	MED0265	MED0266	MED0267	MED0268	MED0269	MED0270
		Gyratory 1 - Bottom	MED0271	MED0272	MED0273	MED0274	MED0275	MED0276	MED0277	MED0278	MED0279	MED0280
		Gyratory 1 - Top	MED0281	MED0282	MED0283	MED0284	MED0285	MED0286	MED0287	MED0288	MED0289	MED0290

COMMENTS:

Master Image List - Medium Specimen Polish

Road: SLR

Mix Type: HL3

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Medium (30 cycles)	20	Core 1	MED0121	MED0122	MED0123	MED0124	MED0125	MED0126	MED0127	MED0128	MED0129	MED0130
		Core 2	MED0131	MED0132	MED0133	MED0134	MED0135	MED0136	MED0137	MED0138	MED0139	MED0140
		Core 3	MED0141	MED0142	MED0143	MED0144	MED0145	MED0146	MED0147	MED0148	MED0149	MED0150
		Gyratory 1 - Bottom	MED0151	MED0152	MED0153	MED0154	MED0155	MED0156	MED0157	MED0158	MED0159	MED0160
		Gyratory 1 - Top	MED0251	MED0252	MED0253	MED0254	MED0255	MED0256	MED0257	MED0258	MED0259	MED0260
		Gyratory 2 - Bottom	MED0171	MED0172	MED0173	MED0174	MED0175	MED0176	MED0177	MED0178	MED0179	MED0180
		Gyratory 2 - Top	MED0181	MED0182	MED0183	MED0184	MED0185	MED0186	MED0187	MED0188	MED0189	MED0190
		Gyratory 3 - Top	MED0191	MED0192	MED0193	MED0194	MED0195	MED0196	MED0197	MED0198	MED0199	MED0200

COMMENTS:

Master Image List - Medium Specimen Polish

Road: DR

Mix Type: HL3

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Medium (30 cycles)	20	Core 1	MED0001	MED0002	MED0003	MED0004	MED0005	MED0006	MED0007	MED0008	MED0009	MED0010
		Core 2	MED0201	MED0202	MED0203	MED0204	MED0205	MED0206	MED0207	MED0208	MED0209	MED0210
		Core 3	MED0021	MED0022	MED0023	MED0024	MED0025	MED0026	MED0027	MED0028	MED0029	MED0030
		Gyratory 1 - Bottom	MED0031	MED0032	MED0033	MED0034	MED0035	MED0036	MED0037	MED0038	MED0039	MED0040
		Gyratory 1 - Top	MED0041	MED0042	MED0043	MED0044	MED0045	MED0046	MED0047	MED0048	MED0049	MED0050
		Gyratory 2 - Bottom	MED0211	MED0212	MED0213	MED0214	MED0215	MED0216	MED0217	MED0218	MED0219	MED0220
		Gyratory 2 - Top	MED0061	MED0062	MED0063	MED0064	MED0065	MED0066	MED0067	MED0068	MED0069	MED0070
		Gyratory 3 - Bottom	MED0071	MED0072	MED0073	MED0074	MED0075	MED0076	MED0077	MED0078	MED0079	MED0080
		Gyratory 3 - Top	MED0081	MED0082	MED0083	MED0084	MED0085	MED0086	MED0087	MED0088	MED0089	MED0090

COMMENTS:

Master Image List - Medium Specimen Polish

Road:

FR

Mix Type:

Microsurfacing Type II

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
Medium (30 cycles)	20	Core 1	MED0091	MED0092	MED0093	MED0094	MED0095	MED0096	MED0097	MED0098	MED0099	MED0100
		Core 2	MED0101	MED0102	MED0103	MED0104	MED0105	MED0106	MED0107	MED0108	MED0109	MED0110
		Core 3	MED0111	MED0112	MED0113	MED0114	MED0115	MED0116	MED0117	MED0118	MED0119	MED0120

COMMENTS:

Master Image List - High Specimen Polish

Road: **POW**

Mix Type: **Superpave 12.5mm FC1**

Date:

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
High (80 cycles)	20	Core 1-1-1	HI0231	HI0232	HI0233	HI0234	HI0235	HI0236	HI0237	HI0238	HI0239	HI0240
		Core 1-1-3	HI0241	HI0242	HI0243	HI0244	HI0245	HI0246	HI0247	HI0248	HI0249	HI0250
		Core 1-1-4	HI0251	HI0252	HI0253	HI0254	HI0255	HI0256	HI0257	HI0258	HI0259	HI0260
		Core 1-1-5	HI0261	HI0262	HI0263	HI0264	HI0265	HI0266	HI0267	HI0268	HI0269	HI0270
		Core 1-1-6	HI0271	HI0272	HI0273	HI0274	HI0275	HI0276	HI0277	HI0278	HI0279	HI0280
		Gyratory 1 - Bottom	HI0281	HI0282	HI0283	HI0284	HI0285	HI0286	HI0287	HI0288	HI0289	HI0290
		Gyratory 1 - Top	HI0291	HI0292	HI0293	HI0294	HI0295	HI0296	HI0297	HI0298	HI0299	HI0300
		Gyratory 2 - Bottom	HI0301	HI0302	HI0303	HI0304	HI0305	HI0306	HI0307	HI0308	HI0309	HI0310
		Gyratory 2 - Top	HI0311	HI0312	HI0313	HI0314	HI0315	HI0316	HI0317	HI0318	HI0319	HI0320
		Gyratory 3 - Bottom	HI0321	HI0322	HI0323	HI0324	HI0325	HI0326	HI0327	HI0328	HI0329	HI0330
		Gyratory 3 - Top	HI0861	HI0862	HI0863	HI0864	HI0865	HI0866	HI0867	HI0868	HI0869	HI0870

COMMENTS: **Core 1-1-5 has a small wet area in the upper left portion of the images.**

Master Image List - High Specimen Polish

Carleton UNIVERSITY

Road:

RR

Mix Type:

HL1 Modified

Date:

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
High (80 cycles)	20	Core 1-1-1	HI0751	HI0752	HI0753	HI0754	HI0755	HI0756	HI0757	HI0758	HI0759	HI0760
		Core 1-1-2	HI0041	HI0042	HI0043	HI0044	HI0045	HI0046	HI0047	HI0048	HI0049	HI0050
		Core 1-1-3	HI0051	HI0052	HI0053	HI0054	HI0055	HI0056	HI0057	HI0058	HI0059	HI0060
		Core 1-1-4	HI0061	HI0062	HI0063	HI0064	HI0065	HI0066	HI0067	HI0068	HI0069	HI0070
		Core 1-2-1	HI0071	HI0072	HI0073	HI0074	HI0075	HI0076	HI0077	HI0078	HI0079	HI0080
		Core 1-2-2	HI0081	HI0082	HI0083	HI0084	HI0085	HI0086	HI0087	HI0088	HI0089	HI0090
		Gyratory 1 - Bottom	HI0761	HI0762	HI0763	HI0764	HI0765	HI0766	HI0767	HI0768	HI0769	HI0770
		Gyratory 1 - Top	HI0101	HI0102	HI0103	HI0104	HI0105	HI0106	HI0107	HI0108	HI0109	HI0110
		Gyratory 2 - Bottom	HI0111	HI0112	HI0113	HI0114	HI0115	HI0116	HI0117	HI0118	HI0119	HI0120
		Gyratory 2 - Top	HI0771	HI0772	HI0773	HI0774	HI0775	HI0776	HI0777	HI0778	HI0779	HI0780
		Gyratory 3 - Bottom	HI0781	HI0782	HI0783	HI0784	HI0785	HI0786	HI0787	HI0788	HI0789	HI0790
		Gyratory 3 - Top	HI0791	HI0792	HI0793	HI0794	HI0795	HI0796	HI0797	HI0798	HI0799	HI0800
		Gyratory 4 - Bottom	HI0151	HI0152	HI0153	HI0154	HI0155	HI0156	HI0157	HI0158	HI0159	HI0160
		Gyratory 4 - Top	HI0161	HI0162	HI0163	HI0164	HI0165	HI0166	HI0167	HI0168	HI0169	HI0170
		Gyratory 5 - Bottom	HI0171	HI0172	HI0173	HI0174	HI0175	HI0176	HI0177	HI0178	HI0179	HI0180
		Gyratory 5 - Top	HI0181	HI0182	HI0183	HI0184	HI0185	HI0186	HI0187	HI0188	HI0189	HI0190
		Gyratory 6 - Bottom	HI0191	HI0192	HI0193	HI0194	HI0195	HI0196	HI0197	HI0198	HI0199	HI0200
		Gyratory 6 - Top	HI0201	HI0202	HI0203	HI0204	HI0205	HI0206	HI0207	HI0208	HI0209	HI0210
		Gyratory 7 - Bottom	HI0211	HI0212	HI0213	HI0214	HI0215	HI0216	HI0217	HI0218	HI0219	HI0220
		Gyratory 7 - Top	HI0221	HI0222	HI0223	HI0224	HI0225	HI0226	HI0227	HI0228	HI0229	HI0230

COMMENTS:

Master Image List - High Specimen Polish

Road: UDHS

Mix Type: Superpave 12.5

Date:

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
High (80 cycles)	22	Core 1	HI0551	HI0552	HI0553	HI0554	HI0555	HI0556	HI0557	HI0558	HI0559	HI0560
		Core 2	HI0561	HI0562	HI0563	HI0564	HI0565	HI0566	HI0567	HI0568	HI0569	HI0570
		Core 3	HI1141	HI1142	HI1143	HI1144	HI1145	HI1146	HI1147	HI1148	HI1149	HI1150
		Core 4	HI0901	HI0902	HI0903	HI0904	HI0905	HI0906	HI0907	HI0908	HI0909	HI0910
		Gyratory 1 - Bottom	HI0591	HI0592	HI0594	HI0595	HI0596	HI0597	HI0598	HI0599	HI0600	HI0601
		Gyratory 1 - Top	HI0602	HI0603	HI0604	HI0605	HI0606	HI0607	HI0608	HI0609	HI0610	HI0611
		Gyratory 2 - Bottom	HI0612	HI0613	HI0614	HI0615	HI0616	HI0617	HI0618	HI0619	HI0620	HI0621
		Gyratory 2 - Top	HI0622	HI0623	HI0624	HI0625	HI0626	HI0627	HI0628	HI0629	HI0630	HI0631
		Gyratory 3 - Bottom	HI0632	HI0633	HI0634	HI0635	HI0636	HI0637	HI0638	HI0639	HI0640	HI0641
		Gyratory 3 - Top	HI0642	HI0643	HI0644	HI0645	HI0646	HI0647	HI0648	HI0649	HI0650	HI0651

COMMENTS: Deleted MED0631

Master Image List - High Specimen Polish

Road: UDH3

Mix Type: HL3

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Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
High (80 cycles)	20	Core 1	HI0521	HI0522	HI0523	HI0524	HI0525	HI0526	HI0527	HI0528	HI0529	HI0530
		Core 2	HI0911	HI0912	HI0913	HI0914	HI0915	HI0916	HI0917	HI0918	HI0919	HI0920
		Core 3	HI0541	HI0542	HI0543	HI0544	HI0545	HI0546	HI0547	HI0548	HI0549	HI0550

COMMENTS:

Master Image List - High Specimen Polish

Road: H174

Mix Type: 12.5mm SMA

Carleton
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Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
High (80 cycles)	20	Core 1-2-1	HI0341	HI0342	HI0343	HI0344	HI0345	HI0346	HI0347	HI0348	HI0349	HI0350
		Core 1-2-3	HI0351	HI0352	HI0353	HI0354	HI0355	HI0356	HI0357	HI0358	HI0359	HI0360
		Core 1-2-4	HI0361	HI0362	HI0363	HI0364	HI0365	HI0366	HI0367	HI0368	HI0369	HI0370
		Core 1-3-1	HI0371	HI0372	HI0373	HI0374	HI0375	HI0376	HI0377	HI0378	HI0379	HI0380
		Core 1-3-2	HI0381	HI0382	HI0383	HI0384	HI0385	HI0386	HI0387	HI0388	HI0389	HI0390
		Core 1-3-3	HI0391	HI0392	HI0393	HI0394	HI0395	HI0396	HI0397	HI0398	HI0399	HI0400
		Gyratory 1 - Bottom	HI0871	HI0872	HI0873	HI0874	HI0875	HI0876	HI0877	HI0878	HI0879	HI0880
		Gyratory 1 - Top	HI0411	HI0412	HI0413	HI0414	HI0415	HI0416	HI0417	HI0418	HI0419	HI0420
		Gyratory 2 - Bottom	HI0421	HI0422	HI0423	HI0424	HI0425	HI0426	HI0427	HI0428	HI0429	HI0430
		Gyratory 2 - Top	HI0431	HI0432	HI0433	HI0434	HI0435	HI0436	HI0437	HI0438	HI0439	HI0440
		Gyratory 3 - Bottom	HI0441	HI0442	HI0443	HI0444	HI0445	HI0446	HI0447	HI0448	HI0449	HI0450
		Gyratory 3 - Top	HI0451	HI0452	HI0453	HI0454	HI0455	HI0456	HI0457	HI0458	HI0459	HI0460
		Gyratory 4 - Bottom	HI0461	HI0462	HI0463	HI0464	HI0465	HI0466	HI0467	HI0468	HI0469	HI0470
		Gyratory 4 - Top	HI0471	HI0472	HI0473	HI0474	HI0475	HI0476	HI0477	HI0478	HI0479	HI0480
		Gyratory 5 - Bottom	HI0481	HI0482	HI0483	HI0484	HI0485	HI0486	HI0487	HI0488	HI0489	HI0490
		Gyratory 5 - Top	HI0491	HI0492	HI0493	HI0494	HI0495	HI0496	HI0497	HI0498	HI0499	HI0500
		Gyratory 6 - Bottom	HI0881	HI0882	HI0883	HI0884	HI0885	HI0886	HI0887	HI0888	HI0889	HI0890
		Gyratory 6 - Top	HI0511	HI0512	HI0513	HI0514	HI0515	HI0516	HI0517	HI0518	HI0519	HI0520

COMMENTS:

Master Image List - High Specimen Polish

Road: **FD**

Mix Type: **HL3**

Carleton
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Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
High (80 cycles)	23	Core 1	HI0661	HI0662	HI0663	HI0664	HI0665	HI0666	HI0667	HI0668	HI0669	HI0670
		Core 2	HI1131	HI1132	HI1133	HI1134	HI1135	HI1136	HI1137	HI1138	HI1139	HI1140
		Core 3	HI0681	HI0682	HI0683	HI0684	HI0685	HI0686	HI0687	HI0688	HI0689	HI0690
		Gyratory 1 - Bottom	HI0691	HI0692	HI0693	HI0694	HI0695	HI0696	HI0697	HI0698	HI0699	HI0700
		Gyratory 1 - Top	HI0701	HI0702	HI0703	HI0704	HI0705	HI0706	HI0707	HI0708	HI0709	HI0710
		Gyratory 2 - Bottom	HI0711	HI0712	HI0713	HI0714	HI0715	HI0716	HI0717	HI0718	HI0719	HI0720
		Gyratory 2 - Top	HI0721	HI0722	HI0723	HI0724	HI0725	HI0726	HI0727	HI0728	HI0729	HI0730
		Gyratory 3 - Bottom	HI0731	HI0732	HI0733	HI0734	HI0735	HI0736	HI0737	HI0738	HI0739	HI0740
		Gyratory 3 - Top	HI0741	HI0742	HI0743	HI0744	HI0745	HI0746	HI0747	HI0748	HI0749	HI0750

COMMENTS:

Master Image List - High Specimen Polish

Road: **OCR**

Mix Type: **HL3**

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
High (80 cycles)	20	Core 1	HI1011	HI1012	HI1013	HI1014	HI1015	HI1016	HI1017	HI1018	HI1019	HI1020
		Core 2	HI0811	HI0812	HI0813	HI0814	HI0815	HI0816	HI0817	HI0818	HI0819	HI0820
		Core 3	HI1021	HI1022	HI1023	HI1024	HI1025	HI1026	HI1027	HI1028	HI1029	HI1030
		Gyratory 1 - Bottom	HI0841	HI0842	HI0843	HI0844	HI0845	HI0846	HI0847	HI0848	HI0849	HI0850
		Gyratory 1 - Top	HI0851	HI0852	HI0853	HI0854	HI0855	HI0856	HI0857	HI0858	HI0859	HI0860

COMMENTS:

Master Image List - High Specimen Polish

Road: SLR

Mix Type: HL3

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
High (80 cycles)	20	Core 1	H10921	H10922	H10923	H10924	H10925	H10926	H10927	H10928	H10929	H10930
		Core 2	H10931	H10932	H10933	H10934	H10935	H10936	H10937	H10938	H10939	H10940
		Core 3	H10941	H10942	H10943	H10944	H10945	H10946	H10947	H10948	H10949	H10950
		Gyratory 1 - Bottom	H10951	H10952	H10953	H10954	H10955	H10956	H10957	H10958	H10959	H10960
		Gyratory 1 - Top	H10961	H10962	H10963	H10964	H10965	H10966	H10967	H10968	H10969	H10970
		Gyratory 2 - Bottom	H10971	H10972	H10973	H10974	H10975	H10976	H10977	H10978	H10979	H10980
		Gyratory 2 - Top	H10981	H10982	H10983	H10984	H10985	H10986	H10987	H10988	H10989	H10990
		Gyratory 3 - Top	H10991	H10992	H10993	H10994	H10995	H10996	H10997	H10998	H10999	H11000

COMMENTS:

Master Image List - High Specimen Polish

Road: DR

Mix Type: HL3

Carleton
UNIVERSITY

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
High (80 cycles)	20	Core 1	HI1041	HI1042	HI1043	HI1044	HI1045	HI1046	HI1047	HI1048	HI1049	HI1050
		Core 2	HI1051	HI1052	HI1053	HI1054	HI1055	HI1056	HI1057	HI1058	HI1059	HI1060
		Core 3	HI1061	HI1062	HI1063	HI1064	HI1065	HI1066	HI1067	HI1068	HI1069	HI1070
		Gyratory 1 - Bottom	HI1071	HI1072	HI1073	HI1074	HI1075	HI1076	HI1077	HI1078	HI1079	HI1080
		Gyratory 1 - Top	HI1081	HI1082	HI1083	HI1084	HI1085	HI1086	HI1087	HI1088	HI1089	HI1090
		Gyratory 2 - Bottom	HI1091	HI1092	HI1093	HI1094	HI1095	HI1096	HI1097	HI1098	HI1099	HI1100
		Gyratory 2 - Top	HI1101	HI1102	HI1103	HI1104	HI1105	HI1106	HI1107	HI1108	HI1109	HI1110
		Gyratory 3 - Bottom	HI1111	HI1112	HI1113	HI1114	HI1115	HI1116	HI1117	HI1118	HI1119	HI1120
		Gyratory 3 - Top	HI1121	HI1122	HI1123	HI1124	HI1125	HI1126	HI1127	HI1128	HI1129	HI1130

COMMENTS:

Master Image List - High Specimen Polish

Road:

FR

Mix Type:

Microsurfacing Type II

Polish Level	Surface Temp.	Specimen	Light 1	Light 2	Light 3	Light 4	Light 5	Light 6	Light 7	Light 8	Light 9	Light 10
High (80 cycles)	20	Core 1	HI0001	HI0002	HI0003	HI0004	HI0005	HI0006	HI0007	HI0008	HI0009	HI0010
		Core 2	HI0011	HI0012	HI0013	HI0014	HI0015	HI0016	HI0017	HI0018	HI0019	HI0020
		Core 3	HI0021	HI0022	HI0023	HI0024	HI0025	HI0026	HI0027	HI0028	HI0029	HI0030

COMMENTS:

APPENDIX A – DETAILED DATA ANALYSIS TABLES AND FIGURES

Table A.1. Relationships Between Gyratory and Field MTD

All Mixes Included	Dense-Graded Mixes Only
Gyratory Top Specimens versus Field Specimens	
$MTD_{Field} = 1.24(MTD_{Top}) - 0.3$ $[R^2=0.93]$	$MTD_{Field} = 0.52(MTD_{Top}) + 0.05$ $[R^2=0.72]$
$MTD_{Field} = 1.14(MTD_{Top})^2 - 0.81(MTD_{Top}) + 0.40$ $[R^2=1.00]$	Polynomial relationship unstable at low MTD
Gyratory Bottom Specimens versus Field Specimens	
$MTD_{Field} = 1.85(MTD_{Bottom}) - 0.38$ $[R^2=0.76]$	$MTD_{Field} = 0.25(MTD_{Bottom}) + 0.21$ $[R^2=0.11]$
$MTD_{Field} = 4(MTD_{Bottom})^2 - 2.8(MTD_{Bottom}) + 0.72$ $[R^2=0.96]$	Polynomial relationship unstable at low MTD

POW	Tukey (HSD)				Tukey (HSD)		
	Contrast	St. Diff.	Crit. Diff.	Sig.?	St. Diff.	Crit. Diff.	Sig.?
	GT vs C	7.757	2.858	Yes	3.250	2.858	Yes
	GT vs GB	6.457	2.858	Yes	2.832	2.858	No
	GB vs C	0.538	2.858	No	0.083	2.858	No
	Category	Groups			Groups		
	GT	A			A		
	GB		B		A	B	
	C		B			B	
	Dunnett (two sided)				Dunnett (two sided)		
	Category	St. Diff.	Crit. Diff.	Sig.?	St. Diff.	Crit. Diff.	Sig.?
	C vs GT	-7.757	2.694	Yes	-3.250	2.694	Yes
	C vs GB	-0.538	2.694	No	-0.083	2.694	No

H174	Tukey (HSD)				Tukey (HSD)		
	Contrast	St. Diff.	Crit. Diff.	Sig.?	St. Diff.	Crit. Diff.	Sig.?
	GB vs C	10.117	2.598	Yes	6.549	2.598	Yes
	GB vs GT	1.160	2.598	No	0.980	2.598	No
	GT vs C	8.958	2.598	Yes	7.530	2.598	Yes
	Category	Groups			Groups		
	GB	A			A		
	GT	A			A		
	C		B			B	
	Dunnett (two sided)				Dunnett (two sided)		
	Category	St. Diff.	Crit. Diff.	Sig.?	St. Diff.	Crit. Diff.	Sig.?
	C vs GB	-10.117	2.439	Yes	-6.549	2.439	Yes
	C vs GT	-8.958	2.439	Yes	-7.530	2.439	Yes

Tukey (HSD)		
St. Diff.	Crit. Diff.	Sig.?
2.921	2.858	Yes
2.698	2.858	No
0.096	2.858	No
Groups		
significance of differences is not transitive		
Dunnett (two sided)		
St. Diff.	Crit. Diff.	Sig.?
-2.921	2.694	Yes
0.096	2.694	No

Tukey (HSD)		
St. Diff.	Crit. Diff.	Sig.?
4.231	2.858	Yes
3.952	2.858	Yes
0.188	2.858	No
Groups		
A		
	B	
	B	
Dunnett (two sided)		
St. Diff.	Crit. Diff.	Sig.?
-4.231	2.694	Yes
0.188	2.694	No

Tukey (HSD)		
St. Diff.	Crit. Diff.	Sig.?
5.345	2.598	Yes
0.981	2.598	No
6.326	2.598	Yes
Groups		
A		
A		
	B	
Dunnett (two sided)		
St. Diff.	Crit. Diff.	Sig.?
-5.345	2.439	Yes
-6.326	2.439	Yes

Tukey (HSD)		
St. Diff.	Crit. Diff.	Sig.?
6.075	2.598	Yes
1.255	2.598	No
7.331	2.598	Yes
Groups		
A		
A		
	B	
Dunnett (two sided)		
St. Diff.	Crit. Diff.	Sig.?
-6.075	2.439	Yes
-7.331	2.439	Yes

SLR	Tukey (HSD)			
	Contrast	St. Diff.	Crit. Diff.	Sig.?
	GT vs C	2.315	3.254	No
	GT vs GB	1.419	3.254	No
	GB vs C	0.652	3.254	No
	Category	Groups		
	GT	A		
	GB	A		
	C	A		
	Dunnett (two sided)			
	Category	St. Diff.	Crit. Diff.	Sig.?
	C vs GT	-2.315	3.043	No
	C vs GB	-0.652	3.043	No

Tukey (HSD)		
St. Diff.	Crit. Diff.	Sig.?
1.218	3.254	No
1.885	3.254	No
0.796	3.254	No
Groups		
A		
A		
A		
Dunnett (two sided)		
St. Diff.	Crit. Diff.	Sig.?
-1.218	3.043	No
0.796	3.043	No

OCR	Tukey (HSD)			
	Contrast	St. Diff.	Crit. Diff.	Sig.?
	GT vs C	9.440	5.891	Yes
	GT vs GB	1.768	5.891	No
	GB vs C	7.275	5.891	Yes
	Category	Groups		
	GT	A		
	GB	A		
	C		B	
	Dunnett (two sided)			
	Category	St. Diff.	Crit. Diff.	Sig.?
	C vs GT	-9.440	5.536	Yes
	C vs GB	-7.275	5.536	Yes

Tukey (HSD)		
St. Diff.	Crit. Diff.	Sig.?
0.066	5.891	No
0.930	5.891	No
1.073	5.891	No
Groups		
A		
A		
A		
Dunnett (two sided)		
St. Diff.	Crit. Diff.	Sig.?
-0.066	5.536	No
1.073	5.536	No

Tukey (HSD)		
St. Diff.	Crit. Diff.	Sig.?
3.208	3.254	No
2.472	3.254	No
0.397	3.254	No
Groups		
A		
A		
A		
Dunnett (two sided)		
St. Diff.	Crit. Diff.	Sig.?
-3.208	3.043	Yes
-0.397	3.043	No

Tukey (HSD)		
St. Diff.	Crit. Diff.	Sig.?
3.318	3.254	Yes
0.285	3.254	No
3.253	3.254	No
Groups		
A		
A		
A		
Dunnett (two sided)		
St. Diff.	Crit. Diff.	Sig.?
-3.318	3.043	Yes
-3.253	3.043	Yes

Tukey (HSD)		
St. Diff.	Crit. Diff.	Sig.?
1.193	5.891	No
0.573	5.891	No
1.894	5.891	No
Groups		
A		
A		
A		
Dunnett (two sided)		
St. Diff.	Crit. Diff.	Sig.?
-1.193	5.536	No
-1.894	5.536	No

Tukey (HSD)		
St. Diff.	Crit. Diff.	Sig.?
0.177	5.891	No
0.897	5.891	No
0.922	5.891	No
Groups		
A		
A		
A		
Dunnett (two sided)		
St. Diff.	Crit. Diff.	Sig.?
-0.177	5.536	No
0.922	5.536	No

DR	Tukey (HSD)				Tukey (HSD)		
	Contrast	St. Diff.	Crit. Diff.	Sig.?	St. Diff.	Crit. Diff.	Sig.?
	GT vs GB	2.091	3.068	No	0.796	3.068	No
	GT vs C	0.760	3.068	No	0.443	3.068	No
	C vs GB	1.331	3.068	No	0.353	3.068	No
	Category	Groups			Groups		
	GT	A			A		
	C	A			A		
	GB	A			A		
	Dunnnett (two sided)				Dunnnett (two sided)		
	Category	St. Diff.	Crit. Diff.	Sig.?	St. Diff.	Crit. Diff.	Sig.?
	C vs GT	-0.760	2.863	No	-0.443	2.863	No
	C vs GB	1.331	2.863	No	0.353	2.863	No

FD	Tukey (HSD)				Tukey (HSD)		
	Contrast	St. Diff.	Crit. Diff.	Sig.?	St. Diff.	Crit. Diff.	Sig.?
	GT vs C	4.104	3.068	Yes	0.852	3.068	No
	GT vs GB	1.904	3.068	No	0.863	3.068	No
	GB vs C	2.201	3.068	No	1.715	3.068	No
	Category	Groups			Groups		
	GT	A			A		
	GB	A	B		A		
	C		B		A		
	Dunnnett (two sided)				Dunnnett (two sided)		
	Category	St. Diff.	Crit. Diff.	Sig.?	St. Diff.	Crit. Diff.	Sig.?
	C vs GT	-4.104	2.863	Yes	-0.852	2.863	No
	C vs GB	-2.201	2.863	No	-1.715	2.863	No

Tukey (HSD)			Tukey (HSD)		
St. Diff.	Crit. Diff.	Sig.?	St. Diff.	Crit. Diff.	Sig.?
1.959	3.068	No	1.763	3.068	No
1.053	3.068	No	0.881	3.068	No
3.012	3.068	No	2.644	3.068	No
Groups			Groups		
A			A		
A			A		
A			A		
Dunnett (two sided)			Dunnett (two sided)		
St. Diff.	Crit. Diff.	Sig.?	St. Diff.	Crit. Diff.	Sig.?
1.053	2.863	No	0.881	2.863	No
3.012	2.863	Yes	2.644	2.863	No

Tukey (HSD)			Tukey (HSD)		
St. Diff.	Crit. Diff.	Sig.?	St. Diff.	Crit. Diff.	Sig.?
0.087	3.068	No	3.883	3.068	Yes
1.326	3.068	No	0.720	3.068	No
1.413	3.068	No	3.163	3.068	Yes
Groups			Groups		
A			A		
A			A		
A				B	
Dunnett (two sided)			Dunnett (two sided)		
St. Diff.	Crit. Diff.	Sig.?	St. Diff.	Crit. Diff.	Sig.?
-0.087	2.863	No	-3.883	2.863	Yes
-1.413	2.863	No	-3.163	2.863	Yes

UDHS	Tukey (HSD)			
	Contrast	St. Diff.	Crit. Diff.	Sig.?
	GT vs C	12.213	2.945	Yes
	GT vs GB	6.772	2.945	Yes
	GB vs C	4.974	2.945	Yes
	Category	Groups		
	GT	A		
	GB		B	
	C			C
	Dunnnett (two sided)			
	Category	St. Diff.	Crit. Diff.	Sig.?
	C vs GT	12.213	2.766	Yes
	C vs GB	-4.974	2.766	Yes

Tukey (HSD)		
St. Diff.	Crit. Diff.	Sig.?
2.123	2.945	No
1.118	2.945	No
0.928	2.945	No
Groups		
A		
A		
A		
Dunnnett (two sided)		
St. Diff.	Crit. Diff.	Sig.?
-2.123	2.766	No
-0.928	2.766	No

RR	Tukey (HSD)			
	Contrast	St. Diff.	Crit. Diff.	Sig.?
	GT vs C	9.048	2.565	Yes
	GT vs GB	7.966	2.565	Yes
	GB vs C	1.394	2.565	No
	Category	Groups		
	GT	A		
	GB		B	
	C		B	
	Dunnnett (two sided)			
	Category	St. Diff.	Crit. Diff.	Sig.?
	C vs GT	-9.048	2.404	Yes
	C vs GB	-1.394	2.404	No

Tukey (HSD)		
St. Diff.	Crit. Diff.	Sig.?
0.452	2.565	No
1.950	2.565	No
1.421	2.565	No
Groups		
A		
A		
A		
Dunnnett (two sided)		
St. Diff.	Crit. Diff.	Sig.?
-0.452	2.404	No
1.421	2.404	No

Tukey (HSD)		
St. Diff.	Crit. Diff.	Sig.?
2.035	2.945	No
2.318	2.945	No
4.513	2.945	Yes
Groups		
A	B	
	B	
A		
Dunnnett (two sided)		
St. Diff.	Crit. Diff.	Sig.?
2.035	2.766	No
4.513	2.766	Yes

Tukey (HSD)		
St. Diff.	Crit. Diff.	Sig.?
1.670	2.945	No
1.741	2.945	No
3.531	2.945	Yes
Groups		
A	B	
	B	
A		
Dunnnett (two sided)		
St. Diff.	Crit. Diff.	Sig.?
1.670	2.766	No
3.531	2.766	Yes

Tukey (HSD)		
St. Diff.	Crit. Diff.	Sig.?
4.608	2.565	Yes
2.036	2.565	No
2.392	2.565	No
Groups		
A		
	B	
A	B	
Dunnnett (two sided)		
St. Diff.	Crit. Diff.	Sig.?
-2.036	2.404	No
2.392	2.404	No

Tukey (HSD)		
St. Diff.	Crit. Diff.	Sig.?
6.490	2.565	Yes
3.632	2.565	Yes
3.001	2.565	Yes
Groups		
A		
	B	
		C
Dunnnett (two sided)		
St. Diff.	Crit. Diff.	Sig.?
-6.490	2.404	Yes
-3.001	2.404	Yes

Table A.3: ANOVA Tests of Change in Friction by Polish Level for Each Specimen Type

Road	Specimen Type	Change in Polish Level (No. of Cycles)									
		0 to 10		10 to 30		30 to 80		0 to 30		0 to 80	
		F-stat	F-crit	F-stat	F-crit	F-stat	F-crit	F-stat	F-crit	F-stat	F-crit
All Roads	C	36.287	3.967	5.538	3.967	9.034	3.967	15.210	3.967	1.031	3.967
	GB	7.829	4.02	8.774	4.02	3.148	4.02	0.054	4.02	1.816	4.02
	GT	1.447	4.013	9.917	4.01	3.619	4.01	4.425	4.01	13.01	4.01
POW	C	2.492	5.318	6.067	5.318	11.947	5.318	17.863	5.318	2.412	5.318
	GB	1.578	7.709	11.636	7.709	22.810	7.709	22.714	7.709	0.580	7.709
	GT	40.373	7.709	3.247	7.709	5.209	7.709	0.046	7.71	68.04	7.71
H174	C	14.327	4.965	7.193	4.965	0.013	4.965	3.808	4.96	3.322	4.96
	GB	0.005	4.965	7.363	4.965	0.329	4.965	9.328	4.96	5.484	4.96
	GT	9.924	4.965	20.930	4.965	2.140	4.965	1.464	4.96	0.037	4.96
SLR	C	8.386	7.709	0.778	7.709	2.835	7.709	2.293	7.71	0.036	7.71
	GB	Insufficient number of samples									
	GT	3.910	7.709	5.851	7.709	77.414	7.709	28.95	7.71	0.723	7.71
OCR	C	95.8	7.709	22.31	7.71	15.24	7.71	30.45	7.71	3.882	7.71
	GB	Insufficient number of samples									
	GT										
DR	C	143.4	7.709	36.98	7.71	7.837	7.71	17.81	7.71	28.35	7.71
	GB	3.67	7.709	20.32	7.71	5.728	7.71	15.85	7.71	72.81	7.71
	GT	0.489	7.709	19.86	7.71	30.42	7.71	18.4	7.71	55.71	7.71
FD	C	32.16	7.709	37.59	7.71	18.89	7.71	13.43	7.71	3.703	7.71
	GB	9.511	7.709	1.867	7.71	0.469	7.71	1.4	7.71	0.619	7.71
	GT	0.346	7.709	15.14	7.71	2.207	7.71	4.033	7.71	1.377	7.71
UDH3	C	19.29	7.709	2.668	7.71	0.055	7.71	11.31	7.71	8.422	7.71
UDHS	C	67.16	5.987	0.322	5.99	0.789	5.99	136.3	5.99	40.67	5.99
	GB	14.54	7.709	13.04	7.71	1.369	7.71	0.447	7.71	0.556	7.71
	GT	0.393	7.709	27.44	7.71	0.005	7.71	17.61	7.71	17.29	7.71
RR	C	97.71	4.965	3.626	4.96	83.84	4.96	146.1	4.96	1.242	4.96
	GB	10.46	4.747	0.913	4.75	2.004	4.75	5.674	4.75	1.193	4.75
	GT	0.096	4.747	0.017	4.75	0.926	4.75	1.964	4.75	2.308	4.75
FR	Cores	18.71	7.709	6.884	7.71	0.372	7.71	0.572	7.71	6.451	7.71

Figure A.1: British Pendulum Number versus Core Light 6 AST

Figure A.2: British Pendulum Number versus Gyratory Bottom Light 6 Average Texture

Figure A.3: BPN versus Core Light 6 AST (Low Polish)

Figure A.4: British Pendulum Number versus Core PTM Z-Vector AST

Figure A.5: British Pendulum Number versus Gyratory Bottom Z-Vector Average Texture