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**The Stripping Susceptibility of Airfield Asphalt Mixes:
The Development of Guidelines for a Laboratory Test Method**

By

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A thesis submitted to
The Faculty of Graduate Studies and Research
in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

The Ottawa-Carleton Institute
Department of Civil and Environmental Engineering

Carleton University
Ottawa, Canada
February 2005

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ABSTRACT

Moisture induced damage (stripping) is defined as the deterioration of a pavement mixture by loss of the adhesive bond between the asphalt binder and the aggregate surface and/or loss of cohesion within the binder primarily due to the action of water. Stripping causes the disruption of mix integrity, which reduces the life cycle by accelerating all distress modes including rutting, fatigue cracking, ravelling, potholes, and flushing.

An extensive literature review has been carried out to identify the main factors leading to moisture-induced damage. Despite the fact that airfield mixes are exposed to the same types of distresses and environmental conditions, the literature shows that most of the research to date is focused on highway asphalt pavements and that it almost ignored the unique characteristics of the airfield asphalt pavements. Moreover, the test methods that are currently used to evaluate stripping in the laboratory showed a lack of correlation to field performance. Therefore, the main objective of this research is to develop guidelines for a laboratory test method that considers the unique characteristics of asphalt mixes used for airfield facilities and to correlate laboratory results to the field performance. In addition, this study examines the relationship between permeability of asphalt surface and stripping characteristics of the mix.

To achieve the objectives of this research, the research plan started by evaluating four major standard test methods, which are currently used to evaluate stripping. The experimental program proceeded by investigating the main factors that affect the evaluation of stripping such as: construction cracks, air voids content, environmental factors, and conditioning duration. In addition, the experimental program investigates the

use of the field permeability as a non-destructive test to evaluate the quality of the laid asphalt pavement in terms of susceptibility to stripping.

Statistical analysis of the test data was performed to examine the significance of the results and to determine a relationship between permeability and stripping characteristics. Finally, the main features of the guidelines for a more reliable test method are proposed and presented. The method was verified using field and laboratory test samples, and preliminary critical permeability limits were determined. This thesis provides the pavement industry and airfield authorities with consistent and more reliable guidelines for a laboratory test method and a non-destructive field test to control and evaluate the susceptibility of airfield mixes to stripping.

ACKNOWLEDGMENTS

The author would like to express his debt to the following persons for their continuous support and encouragement throughout this thesis:

My supervisor, Dr. Abd El Halim for his valuable guidance and scientific advice. The work presented in this thesis would not have been completed without the time and efforts invested by him. My Co-Supervisor, Dr Said Essa, for his encouragement and support.

The Egyptian government, Carleton University, and NSERC for their financial sponsorship during my Ph.D. study period. In addition, Public Works Government Services Canada (PWGSC), National Research Counsel (NRC), and City of Ottawa Laboratory staff due to their support and providing the research with material and test facilities.

The professors and staff of the Civil and Environmental Engineering Department at Carleton University for their support and especial thanks for Dr. Yasser Hassan for his support, guidance, and scientific advice during my research work. Also, thanks to my colleagues in the Civil and Environmental Department for their help and support, and special thanks for the Staff of the Civil and Environmental Engineering Laboratory for the technical support provided throughout my experimental study.

A great endless appreciation and thanks to my parents, brothers, and sisters for their spiritual support and prayers for successful completion of my thesis.

Finally, I would like to acknowledge and offer special thanks to my wife (Halla), and my sons (Ezzeldin, Yusuf, and Ali) who suffered the many cold winter nights waiting for my late arrival to assure me that my hard work is worth the sacrifice for better future.

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ABBREVIATION

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Content
AI	Asphalt Institute
AMIR	Asphalt Multi-Integrated Roller
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Material
AV	Air Voids
BRD	Bulk Relative Density
CLC	Carleton University Civil Engineering Laboratory
CS	Compression Strength
CSR	Compression Strength Ratio
CSRP	Canadian Standards and Recommended Practices
DI	Durability Index
ECS	Environmental Conditioning System
FHWA	Federal Highway Administration
G_{AGG}	Specific Gravity of Aggregate
HL	Hot Laid Asphalt
HMA	Hot Mix Asphalt
ITS	Indirect Tensile Strength
JMF	Job Mix Formula
M_R	Resilient Modulus
MRD	Maximum Relative Density

M_RR	Resilient Modulus Ratio
MS	Marshall Stability
MSR	Marshall Stability Ratio
MTO	Ministry of Transportation of Ontario
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NMAS	Nominal Maximum Aggregate Size
NRC	National Research Council
NSERC	National Sciences and Engineering Research Council of Canada
PWGSC	Public Works Government Services Canada
SHRP	Strategic Highway Research Program
SM	Shear Modulus
SMR	Shear Modulus Ratio
SPSS	Statistical Package for Social Science
Sr	Degree of Saturation
SS	Shear Strength
SSR	Shear Strength Ratio
TSR	Tensile Strength Ratio
TSR_c	Tensile Strength Ratio Due to Cooling Water Bath
TSR_w	Tensile Strength Ratio Due to Warm Water Bath
VMA	Voids in Mineral Aggregate

1 INTRODUCTION

1.1 OVERVIEW

Moisture-induced damage of the bond between asphalt cement and aggregate in asphalt concrete mixtures has been recognized as one of the most critical problems in asphalt pavements. Asphalt stripping is characterized by a loss of adhesion and/or cohesion between the bituminous cement and the aggregate. This problem occurs in the presence of water; therefore stripping is referred to as moisture damage. Stripping attacks pavements in a serious manner, causing a complete failure in its serviceability in a relatively short period of time (Kandhal, 1992). This problem affects thousands of miles of paved roads in the United States, Canada, and around the world (Scarlett 1995, Huang 1993, and Kandhal 1992). Repair of the damaged roads costs local, state, and federal highway agencies billions of dollars every year. These sums are not difficult to imagine if we consider that according to data obtained in 1990, the United States had 2.2 million miles of paved roads with a total asphalt-surface of 94% (Huang 1993). Therefore, it is of strategic importance to predict and investigate how the damage induced by moisture occurs.

The design of asphalt concrete mixtures is a systematic process that involves the selection of asphalt and aggregate materials and proportioning them to provide an appropriate compromise among several variables that affect mixture behaviour. Therefore, the following concerns influence the decision of the designer:

- Reducing or controlling stripping.
- Reducing rutting.
- Minimizing ravelling, potholes, and flushing,

- Maximizing fatigue life.
- Reducing different types of cracks.
- Minimizing the rate of age hardening.

A large number of transportation agencies in North America have reported that stripping can be a significant issue in most pavement distresses, such as rutting, fatigue cracking, ravelling, potholes, and flushing. It may also cause thermal and reflective cracking (Hicks 1991). In addition, Canadian airfield asphalt concrete pavements, especially in the Atlantic, Central, and Pacific regions, show evidence of stripping due to moisture susceptibility. As a result, the anti-stripping agents are used in up to 50% of the laid mixes (Scarlett 1995), which inflates construction costs and does not directly address the problem.

An extensive literature review has been carried out to identify the main factors governing moisture induced damage, including the most promising adhesion theories and stripping mechanisms. In addition, the literature review covers both, prediction methods and prevention techniques of asphalt mix stripping, respectively.

Despite the fact that airfield mixes are exposed to similar damage and environmental conditions, the literature shows that most of the research to date is focused on highway asphalt pavements. This situation reflects a lack of research on airfield asphalt pavements, which have their own unique characteristics (CSRP 1996, MTO 1998, and 1996, AASHTO 1991, 1989, and 1984, and ASTM 1992, 1991, 1988, and 1980). Some of the main differences between airfield and highway mixes are; the asphalt content is higher in airfield mixes than highway mixes, the airfield specifications require maximum relative density 98% while it is 95% for highways, and finally, the gradation of airfield

mixes is finer than those of highways mixes. In addition, one of the most serious issues in the field is that the standard test methods, which are used to evaluate stripping, are neither consistent nor correlated to the field (Mostafa et al. 2004, Mostafa et al. 2003, Solaimanian et al. 2003). The main objective of this research is to develop guidelines for a new test method that is relevant to the unique characteristics of asphalt mixes used for airfield facilities. The proposed test method would be rapid, simple, economical, reliable and correlated to the long-term performance. In order to develop a test method that can fulfil these requirements, a research plan has been proposed to highlight the disadvantages of the existing standard tests and to recognize the unique characteristics of airfield asphalt pavement mixes.

The research plan is mainly based on an experimental program consisting of five Phases designed to achieve the objectives of the present research. The research plan starts with an in-depth literature review that covers the following: factors affecting the problem of stripping, a clear definition of the terms describing the problem of stripping, background information on airfield pavements, and the main differences between the major standard laboratory test methods that are currently used to evaluate moisture-induced damage.

The experimental program is divided into laboratory and field investigations. The laboratory investigation covers the parametric investigation based on a laboratory-testing program that was devised to quantify the influence of the following variables: (1) construction factors (hairline cracks and air voids content), (2) environmental factors (freezing thaw cycles and degree of saturation), and (3) test duration (warm and cool water bath duration). In addition, the results of the laboratory investigation are utilized to

assess and select a suitable test method that could be used to examine mechanical properties of the tested samples during moisture-induced damage evaluation. The outcomes of this investigation are used to develop the main features and guidelines of the new laboratory test method.

The main objective of the field investigation is to examine and model the relationship between permeability and stripping. Furthermore, the objective of the final phase of the research plan is to validate the developed guidelines and to determine the relationship between permeability and stripping, which could be used to determine the critical permeability limits. The outcomes of the laboratory and the field investigations are expected to provide the asphalt pavement industry with a more reliable quality control tool (laboratory guidelines) and a non-destructive quality assurance tool (the permeability limits).

1.2 PROBLEM DEFINITION

Moisture induced damage (stripping) of asphalt concrete mixture is a major form of distress that considerably affects the long-term performance of pavements. Asphalt stripping is a phenomenon in which the asphalt cement in an asphalt pavement loses its ability to bond the aggregate and where the pavement consequently loses its structural strength. The result is a pavement that fails under ordinary traffic loads (Kandhal 1992). These failures, manifesting themselves in the form of alligator cracking, potholes and surface ravelling, typically progress from the bottom of the pavement layers up to the top (Kandhal 1992). Moreover, factors such as inadequate compaction and inadequate drainage can also induce premature stripping (Kandhal 1992).

Different types of testing methods are currently available and range from the simple and inexpensive to the fast, complex, expensive and time-consuming. In addition, there is often a lack of correlation between laboratory results and field performance. Therefore, the test results can be affected by the cost, the experience of the personnel performing the test, and, more importantly, the time required to achieve the test (Hassan et al. 2002). Moreover, it is necessary to have proper knowledge of the unique characteristics of airfield asphalt mixes, including their moisture susceptibility and the factors affecting them in order to remedy the problem. Therefore, laboratory and/or field test methods are needed in order to aid the asphalt pavement industry in evaluating the susceptibility of airfield asphalt pavements to moisture-induced damage.

1.3 RESEARCH OBJECTIVES AND SCOPE

The proposed research aims to investigate the general mechanisms and parameters affecting stripping of airfield asphalt mixes. More specifically, it is necessary to develop guidelines for a reliable test method that could be used to determine the degree of susceptibility of airfield asphalt pavement mixes to moisture-induced damage under Canadian environmental conditions. In addition, the research examines the relationship between permeability and stripping. The main objectives of this research are:

1. To investigate and define the causes of the problem of moisture induced damage with respect to airfield asphalt mixes.
2. To investigate the reasons of the poor correlation between laboratory results and field performance with regards to moisture induced damage.

3. To develop guidelines for a reliable test method that could be used to evaluate moisture susceptibility of airfield asphalt mixes.
4. To study the relationship between permeability and the characteristics of the in-service asphalt mat.
5. To assess the relationship between permeability of in-service pavements and their susceptibility to stripping.

1.4 RESEARCH APPROACH

An intensive literature review has been carried out to provide a better understanding of the nature of the stripping problem and to determine the most promising theories that explain the stripping phenomenon, including the mechanisms that govern it. More importantly, the review covers the main factors that affect the process of assessing moisture induced damage and the reliability of current testing procedures. The literature review shows that there is a relationship between permeability and field density. In addition, the relationship between permeability of in-service pavements and susceptibility to stripping has been identified as one of the objectives of this research and therefore must be examined. The research plan in Figure (1-1) starts with a literature review and continues with the main phases of the experimental program. The literature review will be covered in details in Chapter 2. First, however, the objectives and phases of the conducted experimental program will be briefly introduced below.

Figure (1-1): Research Plan

1. The objectives of phase 1 are:

- To examine the material characteristics of the mixes in accordance with the Public Works Government Services Canada (PWGSC) specifications.
- To prepare samples from different airfield mixes for use in the present work.
- To select the appropriate standard test methods accepted worldwide, and to examine their ability to predict moisture-induced damage for airfield asphalt pavements.

2. The objectives of phase 2 are:

- To evaluate the effect of the construction factors, such as air voids content and surface hairline cracks, on moisture induced damage.
- To investigate the effect of the conditioning process, including warm water bath duration, soaking temperature, and cooling water bath duration, on test quality and duration.
- To evaluate the influence of the environmental factors, like freeze-thaw cycles and moisture content, on the susceptibility of the airfield asphalt pavement mixes.

3. The objectives of phase 3 are:

- To examine different test methods that are used to evaluate the mechanical properties of the tested samples.
- To set new guidelines based on the results obtained from phase 2 and 3.

4. The objective of phase 4 is:

- To investigate the relationship between field permeability and the characteristics of the laid asphalt pavement mixes.

5. The objectives of phase 5 are:

- To verify the ability of the developed guidelines to predict stripping for field and laboratory samples.
- To evaluate the capacity of the developed guidelines to predict the effect of air voids content.
- To compare the results of the developed guidelines and the current standards results.
- To develop the relationship between permeability and stripping, and subsequently determine the critical permeability limits.

1.5 CONTRIBUTIONS OF THIS THESIS

The proposed research presented herein provides engineers and managers of airport pavement facilities with new tools and a body of knowledge that is of crucial importance to reduce costs associated with maintenance and reconstruction of airfield pavements. In addition, reducing the frequency of reconstruction would result in fewer delays of airport operations. More specifically, the research proposed in this study has contributed the following:

1. The development of guidelines for a simple and fast economical laboratory test method that is correlated to the field and that evaluates moisture-induced damage for airfield asphalt mixes. The developed test method will also lead to:

- Minimizing the test duration and simplifying the procedure.
 - Including the effects of the construction factors in the developed guidelines that may lead to a positive correlation between laboratory results and field performance.
2. The development of a model for the relationship between permeability and mix characteristics. In addition, a relationship between permeability and stripping has been determined and presented in this thesis.
 3. The determination of critical permeability limits that can be used with other quality assurance tools to evaluate the quality of the laid asphalt pavement mixes.

1.6 THESIS ORGANISATION

The thesis starts with a brief abstract that is followed by acknowledgements. The thesis proceeds with the table of contents, list of tables, list of figures and is followed by eight main chapters. Finally, the references are listed and seven appendices are attached. The following are the outlines of the contents of the chapters and the appendices.

Chapter 1 introduces an overview, problem definition, main research objectives, scope of the research, research approach, expected contribution, and thesis organisation.

Chapter 2 includes an intensive literature review on moisture induced damage and permeability of asphalt mixes. The main factors contributing to moisture-induced damage of asphalt pavement mixes are identified. In addition, test facilities to perform the experimental investigation are outlined.

Chapter 3 presents the properties of the asphalt pavement mixes, the facilities and

verification of the ability of the current standard test methods to predict stripping.

Chapter 4 presents the parametric investigation (Phase 2) and evaluates the mechanical properties of the tested samples using different test methods (Phase 3).

Chapter 5 shows the analysis of the results from Phase 2 and 3, which is then used to develop the guidelines for the new test methods.

Chapter 6 includes the investigation of the permeability phenomenon and its relation with the characteristics of the laid asphalt pavement mix. The investigation was divided into the laboratory pilot study and the field investigation. The analyses of both investigations are presented.

Chapter 7 introduces the results due to: (i) the verification of the developed guidelines, (ii) examining the relationship between permeability and stripping, and (iii) determining the critical permeability limits that could potentially be used as quality assurance guidelines.

Chapter 8 summarizes the main conclusions of the present work and lists the main issues for future work.

References are presented in alphabetical order at the end of the thesis.

Appendix 1 includes the mix design and characteristics of the used mixes.

Appendix 2 presents the physical properties of the samples tested in phase 1.

Appendix 3 includes samples of the detailed calculation for phase 1.

Appendix 4 presents a sample of the detailed calculations for each factor investigated during phase 2 and phase 3.

Appendix 5 presents samples of the statistical and regression analysis of phases 2 and 3.

Appendix 6 presents the characteristics of the used mixes and samples of the regression analysis output.

Appendix 7 includes the detailed calculations of phase 5.

2 LITERATURE REVIEW

2.1 INTRODUCTION

The presence of water induced damage in the pavement structural system has been known for a long time through extensive visual observations. In 1938, it was reported that stripping of asphalt from mineral aggregate surface in presence of water induced damage is not a new phenomenon (Asphalt Institute 1987), which means that moisture induced damage has been known for more than seventy years (Kiggundu et al. 1988). The importance of moisture susceptibility of asphalt concrete mixtures has been addressed in a long volume of publications and research work; however, it was reported that moisture induced damage has increased (Parker et al. 1986), which reflects the complexity and the difficulty of solving this problem (Kiggundu et al. 1988). According to Jirnez, "All stripping failures have been associated with the presence of water (Jirnez 1974). The stresses that cause failure of asphalt film are assumed to be water pressure and erosion caused by traffic or thermal cycles or both on wet pavements". Lottman et al. reported the possibility to have a disintegrated pavement layer caused by moisture damage (Lottman 1974). In addition, Canadian airfield asphalt concrete pavements, especially in the Atlantic, Central, and Pacific regions, exhibit stripping due to moisture susceptibility. As a result, anti-stripping agents are used in up to 50% of the total laid mixes (Scarlett 1995).

Moisture induced damage of asphalt concrete mixtures is a major form of distress that affects the long-term performance of the laid asphalt pavement mixes. Furthermore, many external and in place properties of the asphalt mix can induce a premature

stripping, such as, inadequate compaction, and inadequate drainage (Kandhal 1992). The main objective of this chapter is to present the following:

- Chemistry of stripping
- The moisture induced damage mechanisms
- Factors that affect moisture induced damage
- Prediction and identification methods of stripping
- Prevention and rehabilitation techniques of stripping
- Permeability definition, factors affect pavement permeability, and its relationship with field performance
- Remarks and recommendations

2.2 CHEMISTRY OF STRIPPING

To understand the stripping phenomenon, it is important to understand the mechanisms that explain how the mix components are bonded. Asphalt mixture consists of two main components, which are the mineral aggregate and the bituminous binder. The main function of the mineral aggregate in the mix is to carry the applied traffic loads as a compressive stress through aggregate interlock, while the main function of the binder is to bond the aggregate particles together as a tensile stress and maintain the system integrity. The properties of each of the aggregate and the binder, as well as the properties of the aggregate-binder system, govern the characteristics and strength of the adhesive bond. Stripping of asphalt pavements is not entirely understood in spite of extensive research that has been done. It is thought to be associated with either one of two phenomena. It is suggested that either the water can interact with bituminous cement to

cause a reduction in cohesion with a subsequent reduction in stiffness and strength of the mix, or water can get between the asphalt film and the aggregate, break the adhesive bond, and strip the asphalt from the aggregate (Hicks 1991) . The nature of the adhesive bond between asphalt and aggregate is a subject of some debate. Adhesion is defined as that physical property or molecular force by which one body sticks to another of different nature (Hicks 1991, Nicholson 1932, and Ishai et al. 1977).

Several factors affect the adhesion of the asphalt cement to the aggregate. These factors include interfacial tension between the asphalt cement and the aggregate, chemical composition of the asphalt cement and aggregate, asphalt viscosity, aggregate morphology, aggregate cleanliness, and aggregate temperature and aggregate moisture content at time of mixing (Scarlett 1995). In addition, several theories have been presented to explain the mechanisms by which the adhesive bond is developed between the aggregate and the binder (Hicks 1991). Four general theories of bonding exist to explain the adhesion of asphalt cement to aggregates. Furthermore, the actual nature of adhesion is partially explained by each theory (Hicks 1991) while combining the adhesion theories may give a full explanation of the adhesion nature. These theories are:

1. The Mechanical Interlocking Theory,
2. The Chemical Reaction Theory,
3. The Surface Energy Theory,
4. The Molecular Orientation Theory, and
5. Combined Adhesion Theory

2.2.1 Mechanical Interlocking Theory

Mechanical interlocking theory assumes that there is no chemical interaction between asphalt and aggregate (Canadian Standards 1996). The bond strength is assumed to be derived from the cohesion in the binder and interlocking properties of the aggregate particles, which include individual crystal faces, aggregate porosity, absorption, surface coating, and angularity (Hicks 1991, Kiggundu et al. 1988, Petersen 1982, and Thelen 1958) as shown in Figure (2-1). Therefore, adhesion between the asphalt cement and the aggregate particles is generally stronger for rougher and more angular particles. In addition, the depth of asphalt penetration into the aggregate pores, and in turn the adhesive bond, increases by separately preheating the aggregate and the asphalt (Scarlett, 1995). This mechanical adhesion, which will be discussed later, is generally compromised by the presence of dust or moisture coating the aggregate particles, which in turn prevent intimate contact between the aggregate and the binder (Hicks 1991, and Petersen 1982).

Finally, it should be noted that trying to improve the mechanical adhesion may lead to more asphalt stripping, which could be explained as follows:

- Excessive surface roughness and irregularities might make it difficult for the asphalt cement to maintain uniform coating of aggregate (Hicks 1991).
- Aggregate pores adsorb smaller oil molecules from asphalt, making the asphalt harder and dryer, and therefore it becomes more susceptible to stripping (Petersen 1982, and Thelen 1958).

Figure (2-1): Effect of Aggregate Surface Texture on Adhesion (Emery and Seddik 1997)

2.2.2 Chemical Reaction Theory

The chemical reaction theory arises from an observation that stripping is more serious in acidic aggregate mixtures as compared to basic aggregate mixtures. In addition, studies have shown that a portion of the binder in asphalt concrete mix is strongly adsorbed by the aggregate such that it can not be extracted by benzene (Petersen 1982). These observations may be attributed to the fact that when the asphalt cement wets the aggregate, adsorption occurs at the surface, then followed by a chemical reaction between the asphalt cement and the aggregate (Lee 1936, Strauss et al. 1942, Saville et al. 1937, Andersland et al. 1952, and Reidel et al. 1953). Furthermore, the mechanical theory alone cannot explain the amount of asphalt that is strongly adsorbed to the aggregate. As a result, it has been argued that following the mechanical interlock; a chemical reaction between the adsorbed asphalt cement and the solid aggregate material takes place (Hicks 1991, and Thelen 1958). According to the chemical reaction theory, the acidic components of the asphalt cement react chemically with the basic aggregate mineral to produce water-insoluble compounds that improve the adhesion between the asphalt cement and the aggregate (El-Khachab 1972, and Ford et al. 1974). It is suggested that the chemical reaction between most of the asphalt cements and the acidic aggregates is

not as strong as the reaction between most asphalt cements and basic aggregates (Hicks 1991). However, it should be noted that some exceptions contradicting the theory of chemical reaction have been recorded, such as an acidic quartzite that has been found to be less susceptible to stripping than most basic aggregates while a basic limestone is known to be susceptible to stripping (Hicks 1991, and Ford et al. 1974).

2.2.3 Surface Energy Theory

When asphalt spreads over and wets an aggregate surface, a change in energy takes place. This change of energy, known as adhesion tension or wetability, is a surface phenomenon that depends on the closeness of contact and common similarity of the asphalt cement and aggregate. The adhesion tension for water to aggregate is higher than that for asphalt to aggregate, and consequently water has a tendency to displace the asphalt from the aggregate (Hicks 1991, Scarlett 1995, and Ford et al. 1974). This wetting ability will depend on the asphalt interfacial tension; low interfacial tension materials are able to cover more surfaces than high interfacial tension materials. This theory can explain the improvement in adhesion properties due to preheating the aggregate as well as the observation that stripping resistance can be improved by leaving the freshly broken aggregates to age (Kiggundu et al. 1988). Preheating the stone will lead to a lower interfacial tension between the asphalt and the stone, which produces a stronger bond between the asphalt and the aggregate (Thelen 1958). If the aggregate is left to age and exposed to cycles of varying temperature and humidity, the outermost water molecules will be partially displaced or covered by organic contamination such as fatty acids (Thelen 1958). Therefore, the new surface will have a lower interfacial tension with the

asphalt, and this will improve the spreading of the asphalt over the aggregate particles and improve the stripping resistance (Thelen 1958).

2.2.4 Molecular Orientation Theory

The molecular orientation theory states that when asphalt cement comes into contact with the aggregate surface, the molecules in the asphalt orient themselves so as to satisfy the energy demands of the aggregate (Hicks 1991). According to this theory, adhesion is the result of a molecular attraction between the asphalt molecules and the outer molecules of the aggregate (El- Khachab 1972, Mohamed 1991, and Mack 1935).

Water molecules are dipolar. Although asphalt molecules are generally non-polar, they contain some polar components. Consequently, water molecules, being more polar, may more readily satisfy the energy demands of an aggregate surface (Kandhal 1992, and Hicks 1991). The polar portion of the asphalt molecules will form a bond with the aggregate surface, which can be strong enough to displace water from the aggregate surface. However, because the polar molecules of the asphalt cement are not dominant, this effect may not be significant (Hicks 1991). Finally, it should be noted that an approach for improvement of the molecular bond and the mechanical adhesion has been suggested through microwave heating of the pavement materials (Al-Ohaly et al. 1988). When the microwaves pass through a material with dipolar molecules, the molecules will act like microscopic magnets and will attempt to polarize with the field. In addition to this polarisation within a material, interfacial polarisation, which is the result of accumulating opposite charges on adjoining surfaces along the interface, will occur (Figure (2-2)) (Al-Ohaly et al. 1988).

Figure (2-2) Polarization Effect on Improving Asphalt-Aggregate Adhesion Using Microwave Heating (Al-Ohaly and Terrel 1988)

2.2.5 Combining Adhesion Theories

Each theory, which has been discussed in the previous sections, partially explains the development of adhesive bond between the aggregate particles and the asphalt cement. Even though, surface energy theory is believed to be the most widely accepted (Asphalt Institute 1987), all theories should be considered to fully define the asphalt-aggregate adhesion, and give an enhanced concept in the analysis of the asphalt stripping phenomenon. The interaction between these theories has been suggested as follows (Yoon et al. 1988):

- (a) The mechanical interlock theory explains the bond strength between the asphalt and the aggregate,
- (b) The wetting behaviour of asphalt is explained by the surface energy concept,
- (c) The degree of stripping depends on the interfacial free energy relationships, and,
- (d) The adsorption of asphalt by aggregate is based on the chemical interaction theory.

2.3 STRIPPING MECHANISMS

Stripping of asphalt concrete mixes, as mentioned before, is an old problem that has been known from the beginning of the asphalt pavement industry. Moisture damage in asphalt concrete pavement is associated with two mechanisms, the first is loss of adhesion and the second is the loss of cohesion. The loss of adhesion is due to water getting between the asphalt and the aggregate. The loss of cohesion is due to softening of the asphalt cement in the presence of water, which weakens the bond between asphalt concrete and the aggregate, and it reduces the adhesive bond between them (Kandhal 1992, and Kiggundu et al. 1988). Moreover, these two mechanisms are interrelated, which means that the moisture damage comes from loss of both cohesion and adhesion even though one of them may override the other.

Based on field observations and laboratory testing, several mechanisms have been suggested to explain how stripping actually occurs, and thus how it can be minimized or eliminated. In general, all of these mechanisms are tied with one of the two phenomena (loss of adhesion or loss of cohesion). These mechanisms are not completely understood and some debate exists to explain the relative contribution of each mechanism to stripping in individual cases. For example, it is probable that the predominant stripping mechanisms in a hot-dry environment differ from the mechanisms in a hot-wet, or a cold-dry, or a cold-wet environment (Kiggundu et al. 1988). Many mechanisms by which stripping occurs have been proposed, but the six most commonly accepted mechanisms are detachment, displacement, spontaneous emulsification, film rupture, pore pressure, and hydraulic scouring.

2.3.1 Detachment

Detachment is the microscopic separation of an asphalt film from the aggregate surface by a thin layer of water with no obvious break in the asphalt film. The asphalt will then strip cleanly from the aggregate (Mohamed 1991). The thin film of water probably results from either aggregate that was not completely dried or possibly water, which permeated through the asphalt film to the interface (Kiggundu et al. 1988). Such a mechanism is based on the theory of surface energy and interfacial tension. The detachment mechanism can also be used to explain blistering and pitting as shown in Figure (2-3). When sun warms the asphalt that is covered with water drops, the warmed asphalt will tend to flow out from under the drop and spread over it forming a blister as shown in the Figure (2-3). As the asphalt gets hotter, the water blister will expand and will eventually break leaving a pit. It should be noted, however, that diffusion of water molecules through asphalt is a very slow process, and therefore is not expected to be a significant factor in stripping and blistering except in the presence of a discontinuity in the asphalt film (Hicks 1991).

Figure (2-3): Blister formation by detachment (Thelen 1958)

2.3.2 Displacement

Displacement occurs when the asphalt is removed from the aggregate surface by water. In this type of stripping, as compared to detachment, the free water gets to the aggregate surface through a break in the asphalt coating. The break may be from incomplete coating during mixing or from asphalt film rupture (Asphalt Institute 1987). In this mechanism, the aggregate, the asphalt, and the free water are all in contact (Ford et al., 1974). Thus, the free water will tend to displace the asphalt from the aggregate surface, where, similar to the detachment stripping mechanism, the displacement mechanism is governed by the surface energy theory of adhesion (Kiggundu et al. 1988). It should be noted that the breakage of the asphalt film could result from incomplete coating or a rupture of the coating film or can be explained in light of the chemical theory of adhesion (Mohamed. 1991). A number of investigations have shown that stripping, and the effectiveness of anti-stripping additives, is strongly influenced by the pH of the contact water suggesting that a chemical reaction has contributed to the stripping phenomenon (Kiggundu 1988, Yoon et al. 1988, Scott 1978; and Hassan et al. 2002). In addition, the use of deicing chemicals was found to influence stripping, suggesting a contribution of a chemical reaction in the stripping phenomenon (McCutcheon et al. 1992). It is known that deicing agents increase the water wetting ability to the aggregate, which may enhance the stripping phenomenon. However, it should be noted that other investigations did not record an effect to the chemistry of the free water on the stripping phenomenon (Fromm 1974).

2.3.3 Spontaneous Emulsification

Spontaneous emulsification occurs when an inverted emulsion (water droplets in asphalt rather than asphalt droplets in water as found in common emulsified asphalt) is formed. This mechanism seems to be enhanced under traffic on mixtures loaded with free water (Kiggundu et al. 1988, and Asphalt Institute 1987). The process can be noted in asphalt concrete mixtures through the formation of grey or grey-brown material, which was proven to be a water-in-oil emulsion (Fromm 1974). The emulsion was found to form spontaneously whenever asphalt films are immersed in water but at a rate dependent on the nature of the asphalt cement and the additives used. The formation of the emulsion is reversible; that is the asphalt regains its original condition upon the evaporation of water (Fromm 1974). Therefore, samples broken after several months of laboratory storage were found to self-heal leaving no or little signs of stripping. However, if the emulsification process is given sufficient time for the emulsion to penetrate the asphalt film coating the aggregate, the adhesive bond will be broken. Another observation suggested that some additives, which are used to improve the initial coating of asphalt cement to the aggregate, can act as emulsifiers. This process can promote breaking the asphalt-aggregate bond through spontaneous emulsification. The emulsifying potential of the anti-stripping additives is usually overlooked in the stripping tests due to the relatively short time for immersion during such tests (Fromm 1974). As mentioned, stripping caused by this mechanism will have a unique characteristic of grey or grey-brown asphalt cement.

2.3.4 Film Rupture

Film rupture, even it is not considered as a stripping mechanism on its own, is believed to initiate stripping. Film rupture is marked by fissures that occur under stresses of traffic at sharp aggregate edges and corners where the asphalt film is the thinnest. Once a break in the film is present, water is able to find its way to the interface and initiate stripping (Kiggundu et al. 1988). As mentioned before, rupture of the asphalt film coating the aggregate initiates stripping (Kiggundu et al. 1988, and Asphalt Institute 1987) and it occurs due to construction loads, traffic loads, freeze-thaw cycles, and/or presence of dust coating the aggregate particles (Kiggundu et al. 1988, and Thelen 1958). Film rupture can also be the result of blistering and pitting as discussed earlier (Thelen 1958). Moreover, spontaneous emulsification, if given sufficient time, will break the asphalt film at its thinnest points (Fromm 1974). If the film ruptures, the water will have an access to the aggregate-asphalt interface causing a displacement stripping (Kiggundu et al. 1988, and Mohamed 1991).

2.3.5 Pore Pressure

A build-up of pore pressure is another possible stripping mechanism. Stripping from pore pressure build-up begins when water is allowed to circulate freely through the interconnected voids of a high void asphalt mixture. Traffic effects cause the void space to be reduced and passage between voids to be closed thus trapping water. The continued action of traffic can then cause pore pressures to build up to the point of stripping the asphalt from the aggregate (Asphalt Institute 1987). In high void mixes, water can reach to the voids within an asphalt concrete mix through several ways, such as runoff through

road surface, capillary rise through the sub-grade, or seepage from ditches (Kandhal 1992), this water can circulate freely through the interconnected voids (Kandhal 1992, and Asphalt Institute 1987). On the other hand, as known from the field observation, traffic loads make the asphalt pavement denser and that closes up the passages between the voids and traps the water inside the voids. A temperature rise after the moisture has been trapped and/or further densification due to traffic loads will cause a pore pressure to build up within the voids of the asphalt concrete mix. It was reported that pore pressure can be higher than the atmospheric pressure (Asphalt Institute 1987). The developed pressure could exceed the adhesive strength of the asphalt-aggregate surface. If that happens, the pressure will break the adhesive bond and the water will flow around the aggregate causing stripping (Asphalt Institute 1987). In a majority of cases, the binder layers will disintegrate first followed by surface layers (Kiggundu et al. 1988). It should be noted that this type of stripping would be evident only in the interior of the asphalt concrete mix, while the exterior sides will not show virtually signs of stripping (Asphalt Institute 1987).

2.3.6 Hydraulic Scouring

Hydraulic scouring occurs in surface courses more than in the lower courses of an asphalt pavement. When the pavement is saturated, wheel action causes water to be pressed into the pavement in front of the tires and to be sucked out behind the tires, which produce mostly surface ravelling. This hydraulic scouring tends to strip the asphalt from the aggregate. This scouring action can be worsened by the presence of dust on the surface of the roadway, which accelerates the scratch of the asphalt film (Kiggundu et al.

1988, and Asphalt Institute 1987). In addition, the asphalt mixes that suffer from this stripping mechanism have a unique characteristic which makes the stripping in this asphalt concentrated in the upper surface course while stripping usually starts in the lower layers of the asphalt concrete pavement and propagates to the surface.

2.4 RELATIONSHIP BETWEEN ADHESION THEORIES AND STRIPPING MECHANISMS

Very little attention has been paid to the interrelationship between the different adhesion theories and stripping mechanisms in relation to the material characteristics. However, a set of relationships has been proposed in an attempt to establish which combination of adhesion theory, stripping mechanism, and the governing material characteristics best deal with the stripping of an asphalt concrete mix (Ford et al. 1974). Subsequently, a better selection of the materials and/or testing procedure can be achieved. Classifying the contributions of each into primary and secondary, Table (2-1) shows the interrelationship between adhesion theories, stripping mechanisms, and material characteristics.

Table (2-1): Proposed Interrelationship between Adhesion Theories, Stripping Mechanisms, and Material Characteristic (Hassan and Abd El Halim 2000)

		Adhesion theory							
		Mechanical interlock		Chemical reaction		Surface energy		Molecular orientation	
		P	C	P	C	P	C	P	C
Stripping mechanism	Operating mode								
	Detachment	**				**	*	*	**
	Displacement				**	**		*	**
	Spontaneous emulsification			**	*				
	Film rupture	**	*						
	Pore pressure	**							
	Hydraulic scouring	**							

P and C are physical and chemical material properties, respectively.

** and * are primary and secondary contributions, respectively.

2.5 GENERAL FACTORS AFFECTING MOISTURE DAMAGE

Publications in the asphalt field agreed that moisture induced damage, or stripping of asphalt cement off the aggregate in an asphalt concrete mix, is associated with the presence of water (Kandhal 1992, Hicks 1991, and Mohamed 1993). However, as the resistance of asphalt concrete mixes to moisture damage, in the presence of water, can vary from very poor to very good, other factors must be contributing to the stripping. The complexity of moisture damage is also evident from the number of factors affecting it. These factors can be classified as follows:

1. Material characteristics,

2. Environmental conditions,
3. Operation and construction effects, and
4. Pavement drainage.
5. Anti-stripping agents

Generally, a factor improving the adhesive bond between the asphalt and the aggregate will also contribute toward reducing stripping and improving the resistance to moisture damage, and vice versa.

2.5.1 Material Characteristics

Based on the discussion on adhesion theories and stripping mechanisms, the characteristics of the materials of asphalt concrete mix can be considered an important factor affecting stripping potential. As mentioned earlier, since the asphalt concrete pavement is a two-component system, its performance, including stripping resistance, will be affected by the characteristics of the aggregate, asphalt binder, and the mix. These characteristics are discussed in the following sub-sections.

2.5.1.1 Aggregate Characteristics

Aggregates are composed of minerals. Each mineral has a characteristic chemical composition and crystalline structure. Several aggregate characteristics have been classified as important to stripping resistance (Hicks 1991). Rock types are identified based upon the mineralogical composition and the formation processes associated with the rock. Important to the stripping mechanism is the classification of an aggregate based upon its affinity for water. Based mainly on their silica content, aggregates can be

classified as hydrophilic or hydrophobic (Hicks 1991). Other chemical characteristics that are found to be beneficial in promoting aggregate-asphalt adhesion include the presence of iron, magnesium, and calcium on the aggregate surface while sodium and potassium are detrimental (Hicks 1991). Other aggregate characteristics have already been identified as being important in improving mechanical adhesion, and in turn reducing stripping potential, such as porosity and surface texture. However, as mentioned earlier, too much porosity can adversely affect the adhesion (Hicks 1991). Furthermore, studies showed that the newly crushed aggregates could improve the stripping resistance (Emery 1997, and Kiggundu et al. 1988). In addition, the aggregate gradation can affect the stripping resistance of the asphalt concrete mix (Hicks 1991). This effect can be explained mainly by the resulting air voids as will be explained later. Moreover, there are three main parameters that can affect the aggregate performance. A brief explanation for each one is given below.

Excessive Dust Coating on Aggregate: The problem created by excessive dust coating on the aggregate is two-fold. First, the presence of dust and clay coatings on the aggregate inhibits intimate contact and complete wetting of the aggregate by the asphalt cement. Because the asphalt is adhere to the dust coating and not the aggregate itself, the bitumen is easily stripped from the aggregate, as illustrated in Figure (2-4). Second, the presence of dust particles enhances the action of scouring under the effects of traffic (Kandhal 1992).

Inadequate Drying of Aggregate: Aggregate that adsorbs water will strip easily if not properly dried. This results from the asphalt being displaced from the aggregate by

the thin layer of water already present. A dry aggregate surface will increase the adhesion with the asphalt cement compared to the wet aggregate surface (Kandhal 1992).

Weak and Friable Aggregate: If a weak and friable aggregate is used in an asphalt mix, degradation is possible during rolling and subsequently under heavy traffic. Degradation exposes uncoated aggregate surfaces, which will easily absorb water and initiate the stripping process (Kandhal 1992).

Figure (2-4): Effect of Moisture or Dust Coating on Adhesion (Emery and Seddik, 1997)

2.5.1.2 Asphalt Binder Characteristics

Even though the asphalt binder characteristics are the most important characteristics in the asphalt mix none of the available publications seems to explain the relationship between the asphalt characteristics and stripping (Hicks 1991). However, some investigations have reported that high-viscosity asphalt cements resist displacement by water more than low-viscosity asphalt cements (Schmidt et al. 1972). While high-viscosity asphalt cements usually have higher concentrations of polar compounds the theory of molecular orientation and the mechanical theory of adhesion are able to explain

the improved resistance to stripping. Moreover, a study showed that the higher the asphalt content, the less the asphalt stripping (Schmidt et al. 1972). This can be explained by the decrease in the air voids and permeability, while an increase in the asphalt film thickness leads to greater resistance to stripping, and/or a combination of both effects (Schmidt et al. 1972). An agreement on the effect of the chemistry of the asphalt cement on the adhesion does not exist. Nonetheless, some studies reported that the aggregate has a tendency to adsorb some asphalt compounds, and they suggest an influence of the asphalt chemistry. Moreover, another study has suggested that some compounds contained in the asphalt are more susceptible to stripping (Schmidt et al. 1972).

2.5.1.3 Mix Characteristics

Although the aggregate and asphalt characteristics are known to affect the moisture damage as presented in the previous sections, the interaction between the mix components can be a dominant factor. Therefore, it has been recommended to study each mix as a unique combination to assess its stripping potential (Ramamurti et al. 1987). Several observations have been recorded regarding the effect of the air voids in the asphalt concrete mix on susceptibility to stripping; Brown et al. (1959) reported that dense-graded hot mixtures should not strip unless there are excessive air voids, moisture, or insufficient asphalt cement. They reported that the most important factor that affects the dense-grade mix is the air void. Lottman (1977) has reported that air voids in asphalt pavement might become water saturated even from vapour condensation due to water in the sub-grade or sub-base. A temperature rise after this saturation can cause expansion of

the water trapped in the mixture voids resulting in significant void pressure when the voids are saturated. It was found that void water pressure may develop at 20 psi under differential thermal expansion of the compacted asphalt mixture and could exceed the adhesive strength at the binder-aggregate surface. If asphalt concrete is permeable, water could flow out of the void spaces under the pressure developed by temperature rise and, in time, relieve the pressure developed. If not, then the tensile stress resulting from the pressure may break adhesion bounds and the water could flow around the aggregate causing stripping. On the other hand, open-graded mixes have been observed to have good stripping resistance (Hicks 1991). Such superficially contradictory observations have been explained using a concept of pessimum void content (Canadian Standards 1996). According to this concept, pavements that have low air voids content (less than 4%) are virtually impermeable as the voids are essentially not interconnected, and therefore the pavements are not affected by moisture. However, when the air voids exceed a critical value, they become larger and more interconnected causing water to flow more easily through the pavement. It appears that stripping can occur in the mid range between these two limits of air voids. This mid range has been referred to as the pessimum voids, i.e. opposite of optimum (Terrel et al. 1993). The concept is represented schematically in Figure (2-5), where the mix's retained strength after conditioning by immersion only or immersion with freeze-thaw against the air voids in the mix. Pessimum voids can represent a concept of quantity (amount of voids in a mix) or quality (size, distribution, and interconnection) as they affect the pavement's performance (Terrel et al. 1993). This definition suggests that the consideration of air voids alone may be inadequate in specifying the mix performance related to stripping as this performance is

significantly influenced by the size, shape, and distribution of the voids (Terrel et al. 1993). Therefore, both air voids and permeability should be used to describe the void quantity and quality, respectively. However, it should be noted that this concept of pessimum voids is based mainly upon testing laboratory compacted specimens. A field investigation on the stripping phenomenon in Ontario has indicated that the effect of air voids on the severity of stripping was almost non-existent (Fromm et al. 1965). Moreover, pavements with approximately 3% air voids suffered more damage due to stripping than pavements with approximately 8% air voids. Also, the investigation showed that the presence of random cracking was correlated with the stripping rating (Fromm et al. 1965).

This latter observation may suggest that pavement permeability, which can result from high percentage of air voids or cracking, is the overriding factor and it should have more attention in the research.

Figure (2-5): Concept of Pessimum Voids (Terrel and Al-Swailmi, 1993)

2.5.2 Construction Effect and Pavement Structure

Pavement construction, specifically compaction, is one of the most important factors that influence its performance as related to moisture damage (Mostafa and Abd El Halim 2004, Mohamed 1993, Mohamed et al. 1993, and Terrel et al. 1993, and Kandhal 1992). Different types of reasoning have been offered to explain the influence of pavement compaction on stripping

A high number of air voids, present in the asphalt layers due to the quality of the compaction, allow the movement of water through these pore spaces. Studies have shown that when the in-place air voids are less than 4% to 5% air voids content; the voids are generally not interconnected and therefore impervious to water (Hicks 1991). While most asphalt mixes are designed to have 3% to 5% air voids, many agencies allow a maximum air voids content of 8% at construction assuming that the remaining compaction will occur under 2 to 3 years of traffic. However, due to poor quality control at construction, which mainly means poor compaction, the design air voids content is never reached. If the pavement remains pervious for an extended period of time, stripping is likely to occur due to entrance of water and hydraulic pore pressures induced by traffic (Hicks 1991). Hallberg (1950) has reported that "required internal water pressure causing an asphalt mixture to have adhesive or internal water pressure causing an inversely proportional to the diameter of the pores. Hallberg stated that densely graded aggregate would help to eliminate failure". Majidzadeh and Brovald (Majidzadeh and Brovald 1966) have also stated that the pore pressure from stresses induced by traffic causes the failure of the binder-aggregate bond. Initially, the traffic stresses may further compress the mixture and trap or greatly reduce the internal water drainage. Therefore,

the internal water is in frequent motion (cyclic) and considerable pore pressure is built up under the traffic action. Mack (Mack 1964) has described the pumping action by which tires cause movement of water in a wet pavement. Mack stated that these forces are far greater than thermodynamic ones, and gave primary importance to the resulting loosening and perhaps emulsification of binder.

The conventional rollers compactor can cause hairline construction-induced cracks, which create passages for surface water to penetrate the pavement layer and thus initiating the stripping problem (Mostafa and Abd El Halim 2004, Mohamed et al. 1993, and Mohamed 1991). Such a finding has been confirmed by measuring permeability of asphalt pavements compacted using conventional equipment, where the measured permeability was considerably high (Rickards et al. 1999). Therefore, the presence of the construction cracks can be detrimental to the pavement's stripping resistance. Finally, too much compaction or using vibratory compaction can break the aggregate particles exposing new uncoated surfaces, especially if weak and friable aggregates are used in the mix (Kandhal 1992). These uncoated surfaces can act as the starting point for asphalt stripping.

The pavement structure can also affect the extent of stripping in the different layers. For example, in late 1970's, several states in the south-eastern United States experienced stripping in the hot-mix asphalt concrete course underlying open-graded asphalt friction course (Kandhal 1992). The explanation offered was that the open-graded course retains greater moisture after rain than conventional mixes. This moisture was pressed into the underlying layer due to traffic loading initiating stripping (Kandhal 1992). The resulting stripping was also aggravated if the open-graded course was

constructed while the underlying course had high air voids content. Such a condition can arise if the open-graded course is constructed shortly after the construction of the underlying course i.e. before densification due to traffic loads, which reduce the initial high air voids content (Kandhal 1992). Another case of pavement structure that can promote stripping is the construction of dense-graded asphalt concrete overlay on deteriorated Portland concrete pavement (Kandhal 1992). Finally, it should be noted that the use of waterproofing membranes and seal coats can also promote stripping if the main source of water is the subsurface as they trap the water vapour in the pavement causing a pore pressure to build (Kandhal 1992).

2.5.3 Environmental Conditions During and after Construction

Environmental conditions that have been noted to influence stripping are the presence of water and cycles of cold and warm temperatures. As mentioned earlier, stripping of asphalt cement off the aggregate in an asphalt concrete mix is associated with the presence of water. Possible sources of this water are runoff through the surface, seepage from ditches through the sides and bottom, or capillary rise from subsurface water. However, upward water movement by capillary flow from subsurface water is considered the most common (Kandhal 1992). The subsurface water can also induce moisture to the pavement through water vapour, especially during warm seasons that can get trapped in the asphalt layer with significantly lower permeability than the base and sub-base courses. With the considerably wide airfield pavements, subsurface water, rising through capillary action or as water vapour, can be particularly detrimental if proper sub-drainage arrangements are not installed. Weather conditions during construction have

been related to stripping behaviour (Hicks 1991). If the weather is cool and wet during construction, moisture damage is more likely to occur. Environmental factors that have been suggested to influence stripping include temperature fluctuations, freeze-thaw cycles, and wet-dry cycles (Hicks 1991).

Considering the Canadian climate, cold temperatures can also significantly influence stripping through one of two different ways. Experimental results showed that samples extracted from crack-free pavements experienced an increase in the indirect tensile strength after soaking and short exposure to a cold temperature of -29°C relative to the dry samples (Mohamed 1993, and Mohamed and Abd El Halim 1993). Such an improvement in the performance, which can be considered as improved bond between the aggregate and asphalt, has been explained by the differential thermal contraction between the asphalt and aggregate (Mohamed et al. 1993, and Mohamed and Abd El Halim 1993). Due to this differential thermal contraction, aggregate particles tend to contract less than the asphalt films coating them. Thus, a compressive stress develops at the asphalt-aggregate interface improving the adhesive bond and reducing the susceptibility to stripping. On the other hand, upon exposure to cold temperatures for long periods, the differential thermal contraction between the aggregate and asphalt subjects the asphalt films coating the aggregate particles to tensile stresses, where these stresses cannot be relieved through flow in the asphalt cement at such cold temperatures. If the resulting tensile stresses are higher than the strength of the asphalt cement, cracking may be induced in the asphalt film, thus initiating stripping (Mohamed and Abd El Halim 1993). Finally, saturated pavements exposed to warm temperatures are believed to experience greater degree of stripping (Mohamed 1993, and Schmidt and Graf 1972). However, as

mentioned earlier, in the absence of moisture warm temperatures can help previously stripped pavements to heal (Fromm 1974). Finally, the use of deicing chemicals for ice and snow control may or may not affect the asphalt performance. Studies showed that deicers, such as urea, which is widely used in Canadian airports, have a significant effect on stripping in asphalt concrete mixes without anti-stripping additives (McCutcheon et al. 1992, Super pave Construction Guidelines 1997, and Hassan et al. 2002); while other studies showed that such an effect does not exist (Fromm 1974).

2.5.4 Pavement Drainage

Inadequate surface drainage and/or subsurface drainage allow the water that is necessary for stripping to occur to remain in the pavement system. As mentioned before, water can enter the pavement layers in numerous ways. Surface water can percolate down from the surface, usually through surface cracks. It can also seep in from the sides and bottom from sources such as ditches or high groundwater. Water can also enter the bottom of the pavement system by the upward forces of capillary or as rising vapour condensation due to water in the sub-grade or sub-base (Hicks 1991). Based on the discussion in the previous section, adequate drainage, surface and subsurface, is essential to minimize the susceptibility to stripping as inadequate drainage provides moisture, or water vapour that is necessary to moisture damage (Kandhal 1992). Adequate pavement drainage should account to drain surface runoff water as well as subsurface water, more critically on wide pavements such as multi-lane highways or airfields.

Cedergren and Lovering have reported that (Cedergren and Lovering 1968) "As the highway system requires the construction of multilane highway to greater widths,

gentler slopes and milder curves in all kinds of terrain, the physical problem of developing stable roads have increased. This is equally true of subsurface drainage. Doubling the road width for example, makes drainage about four times as difficult. Barber and Sayer in 1952 have studied the highway sub drainage in great detail. They have reported that even after drainage a dense-graded material will hold considerable water by capillary if protected from evaporation. Water may also move through a soil as a vapour and a considerable amount may be transferred by convection. If water evaporates continuously from the surface, the soil will dry out enough to establish a tension gradient sufficient to maintain the flow required for continuous operation (of evaporation). If evaporation stops, due to covering the surface, the moisture increases toward the value for static equilibrium. Rates of flow due to capillary action may be much greater than those due to gravity alone, especially for clay (Barber and Sayer 1952). They also mentioned in their research (Barber and Sayer 1952) "that the permeability of Portland cement concrete without cracks or honeycombed structure is of magnitude of the permeability of clay samples A-6 and A-7. Low permeability was found in the field for bituminous mixtures due to traffic compaction particularly near the surface". Lovering and Cedergen (1962) have reported, "With insufficient drainage, water may flood the base and rise through the pavement. Many drainage problems and deteriorate pavement can be attributed to water that enters the structural section from below. Ground water is most troublesome in areas where the road grade is near or beneath the surrounding ground water level."

2.5.5 Use of Anti-Stripping Agents

Interest in additives to improve the adhesion between the asphalt cement and the aggregate particles, as well as to reduce asphalt stripping, can be dated back to late 1930's. By the late 1940's, almost 150 chemical compounds were recognised as potential anti-stripping additives, but most of them were never used because of practical consideration (Endersby et al. 1947). Currently, most anti-stripping agents are either common substances such as lime or chemical compounds, and are added to the mixture either as a liquid, powder, or slurry additive.

The general idea for using anti-stripping additives is to prevent or minimise moisture damage by increasing the wetting of the aggregate surface by the asphalt cement or by improving the bond at the asphalt aggregate interface. Some chemicals are soluble in the asphalt cement, and at the same time they have the ability of lowering the surface tension of its solvent. Consequently, using these additives, usually known as surface-active agents or surfactants, can increase the ability of the asphalt cement to wet solid surfaces. Other types of additives are used to alter the acidity or alkalinity of the aggregate surface to provide better adhesion to the acidic or basic asphalt cement, respectively. Inert mineral filler, such as hydrated lime, were also found to help neutralise the aggregate's acidic surfaces to provide better adhesion with asphalt cement.

When selecting an anti-stripping agent, a number of variables have to be addressed (Tunnickliff and Root 1984). These variables include the characteristics of both the aggregates and the asphalt cement. It was indicated that there is no aggregate type that always strips and no aggregate type that never strips. Based on the findings of a comprehensive field investigation, the long-term performance of asphalt concrete

mixtures treated with anti-stripping additives was satisfactory in most cases (MTO 1998). The study also showed that anti-stripping additives have a considerable effect on the aged asphalt mixture that differs from untreated mixes. Finally, caution should be exercised in selecting the type and amount of anti-stripping additive in the mix as some additives that improve the initial bond between the asphalt cement and the aggregates were found to promote stripping at a later stage by acting as emulsifying agents (Fromm 1974). Such an effect was noted to be difficult to detect using current stripping tests that last for a considerably short period of time.

2.6 PREDICTION AND IDENTIFICATION OF MOISTURE INDUCED DAMAGE IN ASPHALT PAVEMENT

The asphalt industry has developed two basic types of tests with regard to asphalt stripping: predictive type tests that test for stripping potential in asphalt mixes and raw materials, and identification type tests that test in-situ materials for stripping in progress. This section will list some of the methods of testing currently being practiced in the industry.

2.6.1 Prediction of Moisture Induced Damage

Numerous laboratory tests exist that are designed to identify paving mixtures that are susceptible to stripping. If a material is identified as being prone to stripping, then the necessary actions can be taken to prevent stripping before it starts. Selecting the most reliable or most effective test method is difficult because the types of pavement distress caused by stripping, such as ravelling or rutting, may be caused by other mechanisms.

Also, field data on stripping tends to describe pavement distress in subjective terms that are difficult to normalize between locations when gathered by different individuals. The most basic requirements of a stripping test are that it always fails mixes, which strip in service and always pass mixes that perform well in the field. Tests for stripping potential may be divided into three types:

- 1) Tests which visually estimate stripping,
- 2) Tests which measure the time-to-disruption of mix specimens stressed in some manner in the presence of water, and
- 3) Tests that measure the change in the mechanical properties of mix specimens exposed to water in some type of conditioning scheme (Asphalt Institute 1987).

The first category includes boiling tests such as ASTM standard method D3625, and static immersion tests such as ASTM D1664. These methods require visual estimation of stripping after the prescribed conditioning. The second category is exemplified by the Texas Freeze-Thaw Pedestal Test (Kennedy et al. 1983). In this test a small asphalt-aggregate sample is immersed in distilled water and monitored until failure while being subjected to repeated freeze-thaw cycles. The third category includes the largest number of tests currently being practiced, such as: Immersion-Compression tests (ASTM D1075), Marshall-Immersion Test, and two versions of indirect tensile test, Lottman version (Lottman 1982), and Tunnicliff-Root version (Tunnicliff and Root 1984). AASHTO or Modified Lottman Test (AASHTO T283), Public Work Government Service Canada (PWGSC ASG 06), Ontario Ministry of Transport Static Immersion Test (MTO LS 283), and the SHRP Test (SHRP 1993) are also widely accepted. In all of these tests, compacted asphalt-aggregate specimens are exposed to conditioning regimes

of varying severity; the ratio of the value of a specific mechanical property, such as compressive strength or tensile strength, measured after conditioning to that before conditioning provides the gauge for stripping damage.

Numerous groups have studied the qualities of the various test methods. Kandhal (Hicks 1991), (Kiggundu and Roberts 1988, Parker 1987, Maupin 1989, Shatnawi et al. 1995, and Bruce 1990) at MDT have all evaluated the relative merits of some or all of the available test methods. Kiggundu and Roberts (1988) ranked the methods tested in their study as follows:

- 1) Lottman test,
- 2) Tunnickliff-root test,
- 3) 10-Minute boil test,
- 4) Immersion-compression test, and
- 5) Nevada dynamic strip test.

2.6.2 Components of Stripping Test

Generally, any of the testing methods that can be used to evaluate the moisture damage in an asphalt concrete mix must have three distinct components (El-Khachab 1972). These components are the specimen, stripping medium, and criterion for evaluation of the degree of stripping.

- **Specimen**

Several types of specimens are used in different moisture susceptibility tests. Some test methods have adopted a loose specimen of aggregate coated with asphalt

cement while other tests employ fully compacted specimens. These compacted specimens, in turn, can be laboratory-compacted briquettes or cores recovered from the field. In addition, the laboratory compacted briquettes can be compacted to the design air voids ratio or to a higher ratio. It should be noted, however, that there is no clear justification for the selection of a specific air voids ratio. A number of concerns relevant to the test specimens can be stated. First, experimental results have shown that tests performed on a specific portion of the aggregate gradation (usually coarse aggregate in loose form) may not provide enough information to predict performance (Skog and Zube 1963). Therefore, compacted specimens that closely simulate the pavement in place on the road are traditionally preferred (Skog and Zube 1963). Furthermore, based on the earlier discussion on the effect of construction on the stripping resistance of asphalt concrete, field-compacted cores should provide a better representation of expected mix performance than laboratory-compacted briquettes.

Laboratory-prepared samples with carefully controlled gradation and asphalt content may not provide a good representation of the variability in gradation, asphalt content, mixing, and compaction experienced in the field (Parker and Gharaybeh 1988). It has been observed that laboratory compaction using Marshall hammer produces briquettes with impermeable or slightly permeable surface (Field and Phang 1967). This observation was explained by the movement of mobile asphalt and fine particles toward the surfaces, due to the build-up of pressure within a briquette caused by the hammer blows, accompanied with rotation of the hammer foot (Field and Phang 1967).

The concern of producing specimens with impermeable surface is also applicable to gyratory-compacted specimens due to the kneading effect. Results of laboratory tests

to measure and compare the moisture damage of Marshall and gyratory-compacted briquettes of the same mix and density showed that gyratory-compacted specimens retained considerably greater strengths than Marshall-compacted specimen (Skabova et al. 1988). As a result, a mix may be accepted or rejected due to its compaction method rather than its true moisture susceptibility.

Marshall hammer can also induce considerable damage to the aggregate in the specimen, thus misrepresenting the field pavement. It should be noted, however, that asphalt specimens have to be prepared in the lab to perform accept/reject test before using it in the field. Finally, the higher air voids ratio suggested in some laboratory-compacted specimens would bring the mix into the pessimum voids range, and thus the evaluated performance of the mix may be significantly inferior to that displayed in the field.

- **Stripping Medium**

Stripping medium or method of conditioning consists of the medium and the procedure under which the specimens are conditioned before testing for stripping and moisture damage. The main guidance in selecting the stripping medium is that it should simulate as close as possible to the field conditions (El-Khachab 1972). Since stripping is associated mainly with the presence of water, all stripping test methods use water or vapour as the stripping medium or the major component of the medium. Although testing specifications require the use of distilled water, previous studies showed that the use of tap water does not affect the result (Fromm 1974). On the other hand, the additional conditioning requirements, which are considered here part of the stripping medium, vary considerably between different stripping tests.

Firstly, it was frequently observed that specimens conditioned in simple immersion can exhibit better performance than that of dry samples (Field and Phang 1967). Such an observation led to the conclusion that simple immersion does not cause enough water to penetrate into the specimen's air voids. Consequently, to ensure a minimum degree of saturation of the tested specimen's some publications recommended vacuum saturation technique (Field and Phang 1967). However, experimental results on investigating the effect of vacuum saturation showed that briquettes subjected to vacuum saturation alone (in dry environment) have, on some occasions, lower retained strengths than the briquettes subjected to vacuum saturation with water immersion (El-Khachab 1972). Such a finding indicates that the process of vacuum saturation alters the mix properties and induces a degree of damage that is not related to stripping (El-Khachab 1972). Furthermore, most of the stripping tests specify a minimum and maximum degree of water saturation for the air voids after the process of vacuum saturation. Although these criteria can be attained through trial-and-error for briquettes with air voids close to the 8% range, it may be impossible to achieve for briquettes with low or high air voids. Studies showed that the minimum saturation level might never be achieved for briquettes with low air voids at any high vacuum level, while the maximum saturation level might be easily exceeded for briquettes with high air voids even with simple immersion only (Terrel and Al-Swailmi 1993).

Secondly, because simple immersion in water at room temperature, even with vacuum saturation, may not be sufficient to induce significant moisture damage, different procedures to accelerate the stripping process have been adopted. Since experimental results showed that moisture damage significantly increases with increasing the

temperature of soaking water (Schmidt 1972, Mohamed 1993, and Field and Phang 1967), emphasis has been added to warm or hot soaking of asphalt specimens. In addition, as discussed earlier, short exposures to cold temperature alone can improve the tensile strength of the mix (Mohamed 1993, and Field and Phang 1967). However, because of potential damage or rupture in the asphalt film at low temperature, some tests have specified the use of freeze-thaw cycles to accelerate the moisture damage. Such a procedure is considered too severe because of the internal pressure that develops during the transition from vacuum freeze to warm soak (Hicks 1991, and Kandhal 1994). It is thus believed that the results from one freeze-thaw cycle can be used to make the initial determination as to the effectiveness of a mixture with or without an anti-stripping additive (Hicks 1991). Finally, the duration of exposure of the specimens to the stripping medium has also been subject to disagreement. Although virtually all test methods specify duration of one to three days, it has been argued that such short duration is not enough to induce moisture damage that is indicative of field conditions (Fromm 1974). However, although a longer duration of exposure to the stripping medium may be well suited for research purposes, it would severely compromise the practicality of the test as a tool for quality control.

- **Criterion for Evaluation of Degree of Stripping**

The third component of a stripping test is the criterion for the evaluation of degree of stripping after the specimen has been exposed to the stripping medium. Generally, the available methods to evaluate degree of stripping can be classified as direct and indirect measurement of stripping (El-Khachab 1972).

The main method to directly measure stripping has been visual examination of loose or compacted specimens. Clearly, such a criterion is subjective and approximate. Visual examination of loose aggregates is also limited to coarse aggregates, where the particles are large enough to allow visual estimation of the stripped zones. However, examining coarse aggregates alone cannot provide good representation of stripping in the actual mix as stripping of fine aggregate is more detrimental to the pavement (Skog and Zube 1963, and Field and Phang 1967).

Previous experience with visual examination of loose aggregate showed that it was impossible to obtain stripping with many asphalt-aggregate combinations that are known to show stripping under field conditions, and vice versa (Field and Phang 1967). Therefore, an improved method for estimating uncoated areas in stripping tests has been suggested and referred to as the mechanical integration method (El-Khachab 1972). More quantitative techniques that are not subject to human error were also developed for direct evaluation of stripping (El-Khachab 1972). Although the procedure is believed to be a sound method, it will not work properly with aggregates that have a very low dye adsorption and high stripping or very high dye adsorption and low stripping (El-Khachab 1972). Because of the difficulties associated with direct measurement of stripping, indirect measurements have been used more widely. The general idea of indirect measurement of stripping is to measure the relative change in a physical or mechanical property of the specimens before and after exposure to the stripping medium (El-Khachab 1972). This relative change can be performed using a destructive test (such as Marshall stability, compressive strength, or indirect tensile strength) or a non-destructive test (such as resilient modulus or elastic modulus using sonic test). Clearly, non-destructive tests

have the main advantage of testing the same specimens before and after stripping as well as the ability to test the specimens after different cycles of exposure to the stripping medium.

2.6.3 Laboratory Stripping Tests

As mentioned earlier, a number of testing methods and criteria have been suggested and adopted in the standards by different agencies. This section presents a brief description of the tests that can be used as a tool for quality control to evaluate a mixture's susceptibility to stripping. For each test, the specimen, stripping medium, and evaluation of degree of stripping are identified. Two main considerations should be borne in mind while discussing these tests: Closeness to simulating field conditions and practicality as a quality control test.

- **Stripping by Static Immersion and Boiling Tests**

The Ontario Ministry of Transportation (MTO) specifies stripping by Static Immersion Test for visual inspection of stripping as Test Method LS-285 (MTO 1996). The test has also been adopted as AASHTO T 182 (AASHTO 1984) and ASTM D 1664 (ASTM 1984), but the ASTM D 1664 was discontinued in April 1993. As shown in Table (2-2), the test specimen is loose coarse aggregate (100 gm passing the 13.2 mm sieve and retained on the 4.75 mm sieve, in case of hot-mix asphalt) coated with 4.0 ± 0.1 gm of asphalt cement. After mixing and cooling, the specimen is immersed in distilled water for 24 hours at 49.0 ± 0.5 °C (stripping medium). Then, the specimen is inspected visually to estimate the percentage of total visible area of the aggregate that has remained

coated (evaluation of degree of stripping). Acceptable mixes must have a minimum retained coating of 65%. Although the test is fairly simple; a number of concerns related to the results of this test have been recorded including the use of coarse aggregate only which is not representative of the mix performance and the test's failure to correlate with the field observations (MTO 1996). The American Society for Testing and Materials (ASTM) adopts the boiling test as standard test ASTM D 3625 (ASTM 1991). As shown in Table (2-2), this test is similar to the static-immersion test (LS-285) by MTO but is conducted at a higher temperature of the stripping medium and for a shorter duration. Although some investigations have reported poor correlation with the field experience, other studies showed a good correlation (Hicks 1991, MTO 1996, and Parker and Wilson 1986). Also, it was reported that the test failed to evaluate the effects of lime as an anti-stripping additive (Parker and Gharaybeh 1988). However, it should be noted that the studies that indicated a good correlation between this tests and field experience were mainly carried out in hot-weather regions (Hicks 1991, MTO 1996, and Parker and Wilson 1986).

- **Marshall Immersion Test**

Marshall Immersion Test is the testing procedure recommended by Public Works and Government Services Canada (PWGSC ASG 06) (PWGSC 1996). As shown in Table (2-3), the test specimens are laboratory-compacted Marshall briquettes at the design percentage of air voids, where at least eight specimens are used in each test. After determining the dry and submerged weight and the specific gravity of each specimen, the specimens are divided into two groups, where both groups have almost equal average

specific gravity. The first group is immersed in water for 30-40 minutes at 60 °C while the second group is immersed in water for 24 hours at 60 °C (stripping medium), after which they are immediately tested for Marshall stability and flow. The specimens are broken open for visual inspection of the extent of cracked or broken aggregate and estimating the degree of moisture damage. Thus, the evaluation of the degree of stripping includes visual inspection but is based mainly on the Marshall stability test, where an index of retained stability is calculated as:

Equation 2-1: Marshall Stability Ratio

$$MSR = \left(\frac{Stability_{con}}{Stability_{un}} \right)$$

where:

MSR = Marshall Stability Ratio

Stability_{un} = the ultimate load at failure for the unconditioned group

Stability_{con} = the ultimate load at failure for the conditioned group

Mixes are accepted if the index of retained stability is not below 75%. Again, this test is fairly simple but some concerns have been raised related to its ability to predict potential stripping. The main concerns are the impermeable surface created by Marshall compaction and the difficulty in getting the water to penetrate the specimen (Field and Phang 1967). As a result, the stripping evaluated in the test may be significantly lower than that occurring under field conditions. Experimental investigations showed that the test could be improved by increasing the warm-soak duration to 14 days and adopting a retained strength criterion based on durability index (DI) (Craus and Ishai 1981).

However, further investigation showed that evaluating the retained strength after six days only (Ishai and Nesichi 1988) could reduce the test duration. MTO adopted the Marshall Immersion Test, with some modifications to the specimen preparation and the stripping medium, as Test Method LS-283 (MTO 1996). In this case, the test specimens are laboratory-compacted but using the double plunger instead of Marshall compaction. Although the percentage of air voids is not specified in the test, the specified compaction effort would yield about 8 to 12% air voids (Emery and Seddik 1997). Six specimens are prepared, weighed to determine the densities, and divided into two groups that have almost the same average density. As shown in Table (2-3), the conditioning procedure is relatively more complex than that of the PWGSC test. Under this test method, several warm air/water bathes with different temperatures are used throughout the test. The table shows also that the stripping medium includes vacuum saturation at 30 ± 1 mm Hg and 25°C for one hour before immersion in a water bath at 60°C for 24 hours. The evaluation of degree of stripping is also based on a visual rating and the percentage of retained stability as calculated in Equation 2.2. The retained stability should not be lower than 70% for the mix to be acceptable. Clearly, this test is more complex than that adopted by PWGSC, and does not address the concern of the effect of vacuum saturation on the retained strength. The visual rating procedure specified in the MTO LS-283 develops the following equation:

Equation 2-2: Visual rating

$$\text{Rating} = \text{PL} + \text{C} + \text{F}$$

where:

PL = 3 when stripping is evident or 4 if stripping is not evident,

C = coarse aggregate factor (0 for less than 10%, 1 for 10 to 30%, 2 for 31 to 60%, or 3 for greater than 60% stripping), and

F = fine aggregate factor (0 for less than 10%, 1 for 10 to 30%, 2 for greater than 30% stripping).

- **Lottman and Modified Lottman Indirect Tensile Tests**

Based on the findings of NCHRP 192 (Lottman 1978) and 246 (Lottman 1982), Lottman developed a testing procedure for stripping potential using indirect tensile strength or diametrical resilient modulus. The American Association of State Highway and Transportation Officials (AASHTO 1989) as standard test AASHTO T 283 (AASHTO 1989) have adopted revised version of the Modified Lottman Test. As shown in Table (2-4), the test specimens are laboratory-compacted briquettes at a 6 to 8% air voids or the level of voids expected in the field. The mixture undergoes a curing process before compaction to simulate ageing. Six specimens are prepared, weighed, and divided into two groups with equal average density. The stripping medium consists of vacuum saturation in distilled water at 25 °C and 254-660 mm Hg for about five minutes and immersion at atmospheric pressure to obtain 55 to 80% degree of saturation. An additional freeze-soak conditioning is achieved by freezing at -18 °C for 16 hours followed by immersion in warm water bath at 60 °C for 24 hours. The evaluation of degree of stripping is achieved using visual inspection as well as indirect tensile strength, where tensile strength ratio is calculated as:

Equation 2-3: Tensile Strength Ratio

$$TSR = \left(\frac{ITS_{ultcon}}{ITS_{ultun}} \right)$$

where:

TSR = tensile strength ratio

ITS_{ultun} = the ITS for the ultimate load at failure for the unconditioned group

ITS_{ultcon} = the ITS for the ultimate load at failure for the conditioned group

Specific minimum TSR is not defined in the standards but a good correlation with the field performance was obtained at a 0.7 TSR (Hicks 1991, Lottman 1978, and Lottman 1982). However, another investigation suggested that to achieve good correlation with field performance the TSR should be raised to 0.8 (Aschenbrener et al. 1995).

- **Tunnicliff and Root Indirect Tensile Test**

The American Society has adopted this test for Testing and Materials (ASTM) as standard test ASTM D 4861 (ASTM 1992, and Tunnicliff and Root 1984). As shown in Table (2-4), the test specimens can be cores extracted from the field or laboratory-compacted briquettes at a 6 to 8% percentage of air voids. Six specimens are prepared, weighed, and divided into two groups with equal average density. The stripping medium consists of vacuum saturation in distilled water at 25 °C and 508 mm Hg for about five minutes to obtain 55 to 80% degree of saturation, followed by immersion in warm water bath at 60 °C for 24 hours. A freeze-thaw cycle is also optional, where the freezing cycle lasts for 15 hours at -18 °C and the thawing cycle lasts at 60 °C for 24 hours. The

evaluation of degree of stripping is achieved using visual inspection as well as indirect tensile strength, where tensile strength ratio is calculated similar to Equation (2-3). Specific minimum TSR is not stated in the standards but an 80% TSR has been shown to provide good correlation with the field performance (Hicks 1991)

- **Other Tests**

In addition to the tests described in the previous sections, a number of other tests have also been developed and some of them are being used by different agencies (Kiggundu and Roberts 1988). Among these tests is the Immersion Compression Test, AASHTO T 165 (AASHTO 1991) or ASTM D 1075 (Canessa 1995), where compressive strength is the mechanical property evaluated before and after conditioning, as well as Texas Freeze- Thaw Pedestal Test that has the unique feature of testing mixtures with fine aggregates only (Kennedy et al. 1983). As part of the Strategic Highway Research Program (SHRP), an Environmental Conditioning System (ECS) has been developed to test the moisture sensitivity of asphalt concrete mixtures (Al-Swailmi and Terrel 1992, and Terrel et al. 1993). The ECS consists of three distinct subsystems that can control water and air flow within the specimen, control the temperature and pressure, and apply static or dynamic load. However, comparison of the ECS results and field performance showed poor correlation, and more research on its use was recommended (Aschenbrener et al. 1995). It should be noted that none of these tests achieve a good correlation with the field performance. Additional tests include Resilient Modulus Test, Double Punch Method, Dynamic Strip Method, Cold Water Abrasion Test, California Moisture Vapour Susceptibility Test, Surface Abrasion Test (Kiggundu and Roberts 1988), Finally, wheel-

tracking tests, that are used mainly to test the rutting resistance, can also be used to test the moisture sensitivity (Terrel et al. 1993, and Prowell and Schreck 2000).

- **Field and Laboratory Identification.**

Testing of in-situ materials is not standardized throughout the industry and tends to be very subjective. This procedure calls for a core to be taken from the pavement section in question, split, visually evaluated, and rated on a scale from 0 to 4. A rating of 4 indicates a good core in which the split surface is shiny and black, and all aggregate particles are coated. A 0 rating characterizes a core in which asphalt is mostly gone from all aggregate surfaces and the core disintegrates upon removal from the cylinder. Marshall Immersed tests as well as MTO LS 283 has used this method as second criteria to evaluate stripping in the lab (Terrel and Al-Swailmi 1993).

2.7 PREVENTION AND REHABILITATION

Two approaches exist for solving the problem of asphalt stripping, a preventive approach and a rehabilitative approach. If there is approach for a complete prevention of stripping that would be the ideal solution. However, it is not realistic, and the real solution most likely will be able to reduce (not prevent) stripping. Below, each approach will be discussed individually.

2.7.1 Prevention

Whether building a new pavement, or overlaying an old one, certain measures should be taken to prevent stripping. Stripping prevention measures can be divided into three categories:

- 1) Material selection,
- 2) Construction practices, and
- 3) Anti-strip additives.

As discussed in the sections on stripping mechanisms and causal factors, several of the factors that lead to stripping are materials related. By choosing materials that are less prone to stripping, some stripping failures can be averted. Certain types of aggregates are especially prone to stripping (Hicks 1991) and should be avoided. Certain types and grades of asphalt cement as well as some asphalt-aggregate combinations are likely to strip (Hicks 1991) and should be avoided. Good construction practices are essential to building pavements that will not strip. Especially important is the need to ensure thorough compaction of the asphalt mat to minimize pore space (Hicks 1991, and Asphalt Institute 1987). The use of anti-strip additives (Kandhal 1992, and Tunnicliff and Root 1984) is actually a materials related issue. While some agencies specify the use of anti-strip additives in all new asphalt mixes, it is probably only necessary to use additives in those mixes that contain materials that are known to be prone to stripping. The Asphalt Institute (Asphalt Institute 1987) has published a comprehensive set of guidelines to help minimize the probability of stripping.

Table (2-2): Summary of Test methods to Evaluate Moisture Induced Damage for Loose Mix (Hassan and Abd El Halim 2000)

	<i>Static immersion test (MTO LS-285)</i>	<i>Boiling water test (ASTM D 3625)</i>
Specimens	100 g aggregate passing the 13.2 mm sieve and retained on the 4.75 mm sieve (hot-mix asphalt concrete) and 4.0 ± 0.1 g asphalt content	Field mixture representation at design asphalt content
Procedure	<ul style="list-style-type: none"> ➤ Place the coated aggregate in a 600 ml beaker and allow to cool at room temperature ➤ Add distilled water in the beaker to about the $\frac{3}{4}$ mark ➤ Place the breaker and contents in a water bath at 49 ± 0.5 °C for 24 hours ➤ Remove from the water bath and estimate the total visible area of the aggregate that remained coated 	<ul style="list-style-type: none"> ➤ Place about 950 ml of distilled water in 1500-2000 ml beaker ➤ Heat to boil, then add mixture ➤ Bring mix back to boil and hold for 1 min ➤ Decant asphalt from vessel and refill with cold water
Analysis	Visual assessment	Visual assessment

Table (2-3): Summary of Tests to Evaluate Moisture Induced Damage for Compacted Samples

	Marshall immersion test (PWGSC ASG-06)	Marshall immersion test (MTO LS-283).
Specimens	Eight specimens divided into two groups; Size: 101.6-mm $\times$ 63.5-mm Marshall briquettes	Six specimens divided into two groups Size: 101.6-mm diameter $\times$ 63.5-mm height Marshall briquettes
Compaction	Marshall hammer with 50 or 75 blows per face	Double plunger
Air Voids	Not specified	About 8 to 12% air voids
Curing	None	Compacted specimens are placed in air bath at 60 °C for 16 to 18 hrs
Procedure	<p>Group I (dry):</p> <ul style="list-style-type: none"> ➤ Test for stability and flow ➤ Break open the specimens for visual inspection <p>Group II (conditioned):</p> <ul style="list-style-type: none"> ➤ Immerse at 60 °C for 24 hours ➤ Test immediately for stability and flow ➤ Break open the specimens for visual inspection 	<p>Group I (air-cured):</p> <ul style="list-style-type: none"> ➤ Soak at 25 °C for 1 hour ➤ Remove and test for stability and flow ➤ Break open the specimens and allow to sit overnight <p>Group II (water-cured):</p> <ul style="list-style-type: none"> ➤ Vacuum saturate in distilled water at 25 °C and 30 mm Hg for about 1 hour ➤ Soak at 60 °C for 24 hours - Soak at 25 °C for 1 hr ➤ Test for stability and flow <p>Break open the specimens and allow to sit overnight</p>
Analysis	- Marshall Stability - Visual examination	- Marshall Stability - Visual examination

Table (2-4): Summary of Tests to Evaluate Moisture Induced Damage for Compacted Samples (Hassan and Abd El Halim 2000)

	Tunncliffe and Root indirect tensile test (ASTM D 4867)	: Modified Lottman indirect tension test (AASHTO T 283)
Specimens	Six samples divided into two groups Size: 101.6-mm diameter × 63.5-mm height (for aggregate ≤ 25.4 mm)	Six samples divided into two groups Size: 101.6-mm diameter × 63.5-mm height (other dimensions can be used if desired)
Compaction	Marshall hammer (ASTM d 1559), California kneading compactor (ASTM d 1561), or Gyratory testing machine (ASTM d 3387)	Marshall hammer (ASTM D 1559), California kneading compactor (ASTM D 1561), or gyratory testing machine (ASTM D 3387)
Air Voids	6 to 8% or expected field level	6 to 8% or void level expected in the field
Curing	Before compaction, mixture for each specimen is placed in a closed container in an oven at the required compaction temperature for 1 to 2 hours.	Before compaction, mixture is cooled at room temperature for 2 hours, placed in a 60 °C oven for 16 hours, placed in a 135 °C oven for 2 hours
Procedure	Sort into groups so average air voids are approximately equal Group I (unconditioned): <ul style="list-style-type: none"> - Store dry at room temperature - Soak for 20 min at 25 °C for temperature adjustment - Test Group II (conditioned): <ul style="list-style-type: none"> - Obtain a 55% to 80% saturation level (50.8 cm Hg for about 5 min in distilled water) - Reject if saturation is > 80% - Soak for 24 hours at 60 °C - Soak for 1 hour at 25 °C for temperature adjustment - Test 	Group I (unconditioned): <ul style="list-style-type: none"> ➤ Water bath at 25 °C for 2 hours ➤ Test Group II (conditioned): <ul style="list-style-type: none"> ➤ Vacuum saturation at 254-660 mm Hg for 5 to 10 min ➤ Submerged at atmospheric pressure for 5 to 10 min ➤ Degree of saturation must be between 55 and 80% ➤ Freeze at -18 ± 3 °C for a minimum of 16 hours ➤ Soak in a water bath at 60 ± 1 °C for 24 ± 1 hours ➤ Water bath at 25 ± 0.5 °C for 2 ± 1 hours ➤ Test
Damage Analysis	<ul style="list-style-type: none"> - Indirect tensile strength - Visual 	<ul style="list-style-type: none"> - Indirect tensile strength - Visual

2.7.2 Rehabilitation

Rehabilitation of a stripped pavement currently includes several possible remedial alternatives. The simplest way is to overlay the stripped pavement with a new asphalt mat. Variations of this simple overlay method involve the repair of deteriorated sections of the old pavement, milling of the existing surface course, placement of a levelling course, or placement of a paving fabric, all before an overlay is placed. The most widely practiced method of rehabilitation involves the complete removal and replacement of the stripped pavement. This is expensive and wastes large quantities of material, but is the only way to ensure that all stripped and stripping-prone material is removed. The most important developments in the practice of pavement rehabilitation involve the use of recycling. Recycling is important because of the reduced environmental impacts associated with reusing the failed material. Many methods of recycling are currently being practiced, including various methods of cold and hot recycling.

2.7.2.1 Cold Recycling

Cold recycling (Epps et al. 1980, Canessa 1995, and Fanning and Day 1995) can include planning or milling of the existing pavement, where the material is then reused as base material in the new pavement structure. It can, also, include the use of rejuvenators that are applied to the existing pavement as stabilizer before the placement of a new wearing surface.

2.7.2.2 Hot Recycling

Hot recycling includes the removal of the failed material, usually by milling, which is then run back through a hot-mix plant, as well as a technique known as hot in place recycling (Button et al. 1994, and Button et al. 1995). Hot in-place recycling is a process that allows the failed pavement to be rehabilitated in-situ. In some cases now, the process can be completed in a single pass. This is beneficial with respect to minimizing disruption of traffic. Current limitations of hot in-place recycle techniques include expensive equipment costs and limited depth of effective rehabilitation. Moreover, particular concerns have been raised as to whether the presence of stripped material in a recycled asphalt mix will accelerate stripping in the new pavement. A study by Amirkhanian and Burati (Amirkhanian and Burati 1992) at Clemson University shows that the use of recycled material in an asphalt mix does not create increased risk of moisture damage in the recycled pavement. Although in all corrective solutions the cause of stripping should be determined and addressed, but this is likely will involve in improving the drainage around the site of the stripping failure.

2.8 PERMEABILITY

The compaction during construction is one of the major factors that affects Hot Mix Asphalt (HMA) pavement; this is due to the initiated hair cracks (Mohamed et al. 1993) and/or the air void left in the layer after compaction (Mohamed et al. 1993, and Robert et al. 1989). It is believed that while hair cracks and air voids content are affecting the asphalt performance; they also affect the permeability, which leads to the moisture

induced damage (Robert et al. 1989). Numerous researches have shown that actual air voids should not be less than 3% or more than 8% (Huang 1993).

Rutting and shoving are two of the distress that could occur due to low air voids while moisture induced damage and cracks occur due to high presence of air voids. Moreover, both dense and coarse graded asphalt mixes suffering from permeability problems. Dense graded mixes start to be highly permeable if air voids are above 8% (Zube 1962) while coarse graded mixes, the air voids is affected by aggregate gradation (Brown 1989). Moreover, number of publications (Kumar and Goetz 1997, Muller 1997, and Kari and Santucci 1963) mentioned that there is a relation between field density and permeability.

2.8.1 Permeability Theory

The term permeability means that a certain fluid (water) can pass through a certain porous media (asphalt layer). Moreover, the permeability follow Darcy's theory (Hlotz and Kovacs 1981) if the flow of the fluid through the media was steady while in case of turbulent flow Darcy's law will be invalid.

Henry Darcy, a French Engineer, has investigated the fundamental theory of permeability. Darcy used clean sand as a medium while water was used as a fluid. The general formula that came up from this investigation was named Darcy's law:

Equation 2-4: Darcy's General Formula

$$q = KiA$$

where:

- q = the flow rate,
- K= permeability (hydraulic conductivity),
- A= cross sectional area of the permeable medium, and
- i = hydraulic gradient

The head is defined as the total water pressure on the specimen and it measured with the height of the water column. The hydraulic gradient is defined as the head loss per unit length; the head loss increases linearly with the velocity of the water through the medium if the flow of water is assumed (and actually) in the laminar state. Finally, it should be noted that aggregate gradation, size, shape, and pore distribution, and temperature (Hlotz and Kovacs 1981) affect the coefficient of permeability (K).

In order to apply the permeability theory, for the asphalt pavement, Darcy's hypothesis assumed to be valid. Furthermore, two techniques could be applied to measure the permeability in the field; the first one is the constant head technique while the second one is the falling head technique. The first technique is applied where there is a material with relatively high permeability such as open-graded friction course (Das 1981) while the second technique is applied if the materiel is relatively low permeable such as the dens-graded HMA (Olson and Daniel 1981). It should be noted that for the constant head technique the equation is shown below.

Equation 2-5: Hydraulic Conductivity using Constant Head Technique

$$K = \frac{QL}{Aht}$$

where:

- K = hydraulic conductivity (permeability)
- Q = total discharge volume of fluid.
- L = length of the sample
- A = cross-sectional area of the sample
- t = time period during which the Q is collected or discharge,
- h = height of the water head on the specimen, and

On the other hand, for the falling head technique the equation will be modified as follows:

Equation 2-6: Hydraulic Conductivity Using Falling Head Technique

$$K = \frac{aL}{At} \ln \left(\frac{h_1}{h_2} \right)$$

where:

- K = hydraulic conductivity (permeability),
- L = length of the permeable medium (asphalt layer thickness),
- A = Cross-sectional area of the sample
- t = time consuming during which the head is allowed to fall,
- h_1 = water head at beginning of the test,
- h_2 = water head at end of the test, and

$a =$ the contact area which the water can go through, (area of stand pipe)

2.8.2 Factors Affecting Permeability of HMA Pavements

As mentioned before, permeability is influenced by a number of factors; compaction is one of these factors (Essa et al. 1993, and Robert et al. 1996). Air voids, and asphalt densities are two components of the compaction results. Moreover, lift thickness, aggregate size (gradation), nominal maximum aggregate size (NMAS), particle shape, degree of saturation, and temperature were found to be the main parameters that affect the permeability measurements (Cooley and Brown 2000). The literature review showed that the falling head technique was used in previous researches to conduct the permeability measurements (Choubane et al. 1998, Kumar and Goetz 1997, Huang et al. 1999, Muller 1997, Maupin 1999, and Cooley 1999) as long as the asphalt mix is relatively highly permeability. The field measurements of the permeability have been conducted by using either air (James 1988, Cechetini 1974, and Kari and Santucci 1963) or water (Mallick et al. 1999, and Cooley and Brown 2000). Previous research showed that field permeability is related to the actual field destiny (Brown et al. 1989, Westerman 1998, Kari and Santucci 1963, and Cooley and Brown 2001).

Construction during summer (high temperature) produces asphalt mat that has much better performance than during any other season. During summer the cracks will seal up due to traffic and thus it reduces the pavement permeability (Zube 1962). It is known that fluid viscosity will change by changing the temperature, which also will affect the measurements. Moreover, Nominal Maximum Aggregate Size (NMAS) was

found to be significantly affect the field permeability and density, this has been confirmed by Cooley and Brown (Cooley and Brown 2001, and Maupin 1999) for different mix types. Furthermore, lift thickness is one of the factors that affect the permeability and asphalt density (Musselman et al. 1998, and Superpave Construction Guidelines 1997). Different researches (Choubane et al. 1998, and Musselman et al. 1998) have recommended ratio of (lift thickness/NMAS) of 4.0 while others (Superpave Construction Guidelines 1997) have recommended a ratio of 3.0.

It should be noted that different studies found that permeability of HMA pavement is directly related to its durability (Kumar and Goetz 1997, Muller 1997, and Kari and Santucci 1963).

2.9 SUMMARY OF THE LITERATURE REVIEW

1. Stripping or moisture-induced damage, of asphalt concrete mixes is a phenomenon that has been observed for a long time and has received considerable attention by pavement engineers and researchers. However, the previous research has focused exclusively on highway pavements, which lead to a lack of research on airfield asphalt mixes.
2. A number of theories have been developed to explain the phenomenon of adhesion between asphalt binder and aggregates in an asphalt concrete mix. While each theory can partially explain such phenomenon, combining all these theories can only provide a good explanation of how asphalt binder adheres to the aggregates.

3. The mechanisms, by which the bond between asphalt binder and aggregates in an asphalt concrete mix can be broken due to moisture, have been explained.
4. The characteristics of aggregate, asphalt binder and the mix are the most important factor affecting moisture sensitivity. Thus, the resistance to moisture-induced damage can be improved by the proper selection of the mix materials, and by proper use of anti-stripping additives.
5. Field construction of asphalt concrete pavements can also be a significant factor influencing the moisture susceptibility of asphalt pavement. Construction cracks resulting from traditional construction equipment provide passages for water to penetrate into the asphalt layer and induce stripping.
6. Environmental conditions are also important factors affecting moisture-induced damage in a specific pavement layer. Not only would rainfall be responsible for the presence of moisture, but also freeze-thaw cycles can produce an initial rupture or weakness in the asphalt film coating the aggregate. Presence of both moisture and initial rupture or weakness in the asphalt film is necessary for moisture-induced damage.
7. The rehabilitation of the stripped pavement using cold recycling or hot recycling techniques has been introduced.
8. There is an essential need for a reliable method for testing moisture susceptibility of asphalt concrete pavements. Such a testing method must be fairly rapid, simple, economic, reliable, and well correlates the field and laboratory observations and results.

9. Permeability is one of the newest techniques that could be used as a quality assurance for the laid airfield asphalt mixes
10. Permeability is affected by several factors such as NMAS, temperature, actual density, actual air voids, and thickness of asphalt lifts.

The literature review completed in this chapter suggested that while pavement engineers and researchers commonly know several laboratory test methods, comparisons between these major test methods are rarely made. Subsequently, researchers and engineers find it extremely difficult to rank these tests, and correlate the results to the field performance. Furthermore, the factors that affect each test procedure need to be examined. The factors that affect each of these tests in terms of sample preparation, environmental effect (freezing thaw), and construction effect (surface cracks), should be discussed, experimentally investigated and evaluated to develop a clear understanding of the ranking and correlations between them. Also, additional testing techniques should be considered to determine the mechanical properties of the test samples. The well known ITS and Marshall stability test methods are no longer sufficient and additional ones such as fatigue, resilient modulus, and direct shear should be considered. Finally, the relationship between the permeability and density should be investigated. This will allow the pavement industry to evaluate the existing and newly constructed pavement using a non-destructive test in relation to their suitability to stripping.

3 EVALUATION OF THE CURRENT STANDARDS

3.1 INTRODUCTION

The main objective of Phase1, of the experimental program, is to compare between the four major standard test methods, which identified during the literature review and to identify their advantages and disadvantages. Figure (3-1) shows the detailed plan of the testing program for Phase1, which includes three main steps. Step 1 examines the characteristics of the mixes that will be used during this phase and throughout the research plan, whereas Step 2 entails the preparation of field samples and laboratory samples from five mixes. Finally, Step 3 will evaluate current standard test methods used to assess stripping. It is important to note that all evaluated mixes are airfield asphalt pavement mixes, which means that PWGSC ASG 06 specifications are considered as a reference for evaluating the characteristics of these mixes.

From the literature review, four standard test methods were selected in order to evaluate their ability to predict stripping; whereas the first two standards are used worldwide, the second two are used in Canada only "AASHTO T283, ASTM D4867, PWGSC ASG 06, and MTO LS 283". In order to perform the evaluation of the aforementioned standard test methods, twenty-six laboratory samples were prepared from each of the examined mixes and the same number of samples were extracted from two field mixes. The results, observations, statistical analysis, remarks and recommendations of this phase are presented at the end of this chapter.

Figure (3-1): Flow Chart of Phase 1

3.2 CHARACTERISTICS OF MIXES

This section discusses the properties of the different mixes that were used during the experimental program. Five pre-specified airfield mixes were examined. Three of the mixes were taken from the MacDonald Cartier Airport (Ottawa, ON), whereas the fourth and fifth airfield mixes were taken from the Penticton Airport (Vancouver, BC). The mix design for these mixes with the job mix formula (JMF) are presented in Appendix 1.

All mixes have been examined according to the PWGSC ASG 06 specifications before being used in the experimental program. The following standards were applied throughout this stage in order to examine the characteristics of the mixes (asphalt content (AC), gradation, maximum relative density (MRD), Bulk Relative Density (BRD), air voids, and void in mineral aggregate (VMA)): ASTM D2172-95, ASTM D 979, ASTM D 5444-98, PWGSC ASG 06, ASTM D 2726-96e1, ASTM D 3203-88, and ASTM D 27041-95.

The procedure started with the extraction and gradation with the purpose of determining asphalt content (AC) and gradation for each of the pre-specified mixes. In addition, the bulk and maximum relative density, the air voids content and the voids in mineral aggregates were measured.

3.2.1 Extraction and Gradation

For each mix, the extraction, gradation, MRD, BRD, Air Voids, and VMA were tested at the City of Ottawa test laboratory. The extraction was checked using the centrifugal force technique (ASTM D2172-95) where trichloroethylene (tri) was used as a

solvent. The test started with the drying of the asphalt mix sample using an oven ranging from 105-115° C in order to eliminate the moisture. Then, the sample was split to receive a representative sample of 1.5kg in accordance with the ASTM D 979 standard testing method. The sample was then put through the centrifugal process and the trichloethylene was added and soaked for 20 minutes. Afterwards, a centrifugal force was applied until all of the “trichloethylene” solution was extracted. This process was repeated two more times before the sample was weighed and the AC was identified as the difference between the original weight and the weight after the test process. The results are presented in Table (3-1). A comparison of the results with the required standards clearly indicates that the mixes pass the standard criteria of the AC.

Testing the gradation was achieved by using a set of sieves following the ASTM D 5444-98 standard test method and comparing the gradation with the PWGSC ASG 06 specifications for both surfaces and base mixes. In addition, the extracted aggregate was washed in order to remove the particles that were finer than the sieve 200 and moreover dried and weighed. Then, the dry aggregate was sieved again, using the mechanical vibrator for 15 minutes. Finally, the retain aggregate was weighed and compared to the percentage pass for each sieve with the upper and lower limits in accordance with the specifications. Table (3-2) presents the gradation of each of the considered mixes, which are found to be acceptable by PWGSC ASG 06 standard specifications.

3.2.2 Maximum and Bulk Relative Densities

This test was completed at the City of Ottawa laboratory according to ASTM D 27041-95 standards for MRD and ASTM D 2726-96 standards for BRD. The test entailed the replacement of air voids found in the loose material or asphalt with water. The replacement of air voids was achieved through the use of a vacuum pump (vessel). The test included the following steps:

- First, the empty flask was weighed. Then, the vacuum flask was filled with the loose sample and was weighed again. It should be noted that the sample weight depends on the maximum particle size. In this case, W1 (1500gm.) represents the flask weight while W2 represents the weight of the flask and the sample.
- Second, the asphalt sample was submerged in water (25° C) and the vacuum vessel was loaded for 20 minutes. The vacuum vessel applied a residual pressure of approximately 30 Hg, which was increased and then decreased gradually.
- Third, the flask and the sample were weighed on a submerged container and the weight was recorded (W3). Then, the MRD was calculated with the use of the following equation:

Equation 3-1: Maximum Relative Density

$$MRD = \frac{(W2 - W1)}{(W2 - W1) - (W3 - W1)}$$

where:

MRD : maximum relative density for asphalt mix, g/cm³,

W2-W1 : weight of oven dried sample in air, g,

W3-W1 : weight of sample in water, g,

- W1 : flask weight, g
- W2 : weight of flask and sample in air, g, and,
- W3 : weight of flask and sample submerged in water after vacuum, g.

Bulk Relative Density (BRD) is defined as the ratio of the mass of a given volume of material to the mass of the same volume of water at 25° C. The test procedure is explained briefly in the following steps:

- The sample is prepared with the use of any facility to make compacted specimen, such as Marshall Compactor.
- The sample is weighed in the air (m1).
- The specimen is submerged in water for 3-5 minutes and the weight is recorded while the sample is being submerged (m2).
- The sample is weighed again in air after the surface is dried from free water, m3.
- The BRD is calculated with the help of the following formula:

Equation 3-2: Bulk Relative Density

$$BRD = \frac{m1}{m3 - m2}$$

where:

BRD : bulk relative density, g/cm³.

m1 : weight of dry specimen in air, g,

m3 : weight of the saturated surface dry specimen in air, g, and,

m2 : weight of the specimen in water, g.

The results of MRD and BRD are presented in Table (3-1). The obtained values of MRD will be used in the next step in order to calculate the content of the air voids for each

sample. Furthermore, the BRD values will be compared with the achieved field density: the field density should be 98% or above of the BRD.

3.2.3 Air Voids and Void in Mineral Aggregate

Air voids are the pores of the air that is entrapped between the bitumen-coated aggregate particles. Air voids are compared to the allowable range in the PWGSC ASG 06 specifications and their content is determined according to ASTM D 3203-88, using the following equation:

Equation 3-3: Air Voids Content

$$Av\% = 100 * \left(1 - \frac{BRD}{MRD}\right)$$

where:

Av : percent of air voids, %.

BRD : bulk relative density, g/cm³, and,

MRD : maximum relative density, g/cm³.

Moreover, voids in mineral aggregates VMA are considered one of the main criteria in the Marshall Mix Design method and are determined using the following formula:

Equation 3-4: Voids in Mineral Aggregates

$$VMA\% = 100 * \left[\frac{BRD * (100 - AC\%)}{G_{agg}} \right]$$

where:

VMA : percent voids in mineral aggregates, %.

BRD : bulk relative density, g/cm^3 ,

AC : asphalt content %, and,

G_{Agg} : specific gravity of aggregate, g/cm^3 .

The results for VMA as well as the A_v are presented in Table (3-1). It should be noted that the main objective of this section is to check the pre-specified mixes according to the specifications (PWGSC ASG 060) before using these mixes within the outlined experiment. Appendix I contains the detailed results for this section.

Table (3-1): The Physical Characteristics of the Mixes

Asphalt Mix Type	Mix1	Mix2	Mix3	Mix4	Mix5
Asphalt Content (Ac) %	5.79	6.06	4.82	6.1	6.1
(MRD) g/cm^3	2.483	2.484	2.518	2.443	2.438
Sample Density (BRD) g/cm^3	2.386	2.439	2.44	2.353	2.2.35
Air voids in total mix %	3.31	3.46	3.18	3.64	3.70
Voids in mineral aggregate.	15.2	15.2	15.0	15.3	15.3
Flow index 0.25 mm	6.683	6.183	6.3	7.54	7.04
Marshall Load N	13350	12708	17609	16185	17609

Table (3-2): The Gradation of the Mixes

Sieve #	26.5	19	16	12.5	4.75	2	0.425	0.18	0.075
Percentage Pass Mix1	100	100	100	99.7	60.7	45.9	25.5	7.8	4.3
Percentage Pass Mix2	100	100	100	99.8	56.8	46.2	26.6	10.5	4.3
Percentage Pass Mix4	100	100	100	100	58.9	45.6	18.8	6.0	1.2
Percentage Pass Mix5	100	100	100	100	58.1	45.6	16.2	5.1	1.1

PWGSC Limits	Upper Limit	100	100	100	100	75	55	30	20	8
	Lower Limit	100	100	100	100	55	35	15	5	3
Percentage Pass Mix3		100	100	100	78.9	45.7	29.3	17	9.2	3.2
PWGSC Limits	Upper Limit	100	100	100	85	60	55	30	20	8
	Lower Limit	100	100	100	75	35	35	15	5	3

3.3 SAMPLE PREPARATION

This section details the preparation of the field and laboratory samples. It should be noted that the field cores were extracted from surface mixes Mix1 and Mix2, while the laboratory samples were prepared from Mix1, Mix2, Mix3, Mix4, and Mix5.

As outlined in the literature review, the preparation of samples for each standard test method requires the relationship between the number of blows and the air voids content. In addition, the relationship between the vacuum duration and the degree of saturation must be determined.

3.3.1 Field Slabs and Cores

To extract cores from the field, four wooden forms were prepared at the Carleton University Civil Engineering Laboratory "CLC". Two forms for each mix type (Mix1 and Mix2) were constructed with the dimensions of 1000mm*1500mm*75mm, as illustrated in Figure (3-2). After the compaction process in the field was completed, the wooden forms were divided into six small square slabs of 50*50 cm for better handling and easier transportation to CLC. Figures (3-3) and (3-4) show the compaction process while Figure (3-5) shows the nuclear gauge measurement after compaction in order to check the achieved density in the field. The forms were left overnight at the site. The

process of cutting the forms, is presented in Figure (3-6) while Figure (3-7) presents the surface cracks resulting from compaction. Core specimens were recovered from the small slabs at CLC; only one form was used for each type of mix, while the second form was kept intact to be used for the laboratory permeability measurements. Ninety-five core specimens were recovered from each of Mix1 and Mix2.

It should be noted that the PWGSC specifications require that the airfield compacted mixes accomplish 98% of the BRD after compaction. This requirement was achieved for Mix1, while Mix2 achieved a BRD of 97%. The extracted cores were stored in the laboratory on a flat surface in order to be used in the next steps. Finally, since the average height of the field cores is 75 mm, the height of the cored samples was adjusted to be 62.5 mm by cutting from the top and /or from the bottom of the extracted cores.

Figure (3-2): The Forms for the Field Slabs

Figure (3-3): Steel Roller Compactor in Process

Figure (3-4): Pneumatic Compactor in Process

Figure (3-5): Checking the Slabs Density Using Nuclear Gauge

Figure (3-6): Process of Cutting the Slabs

Figure (3-7): Surface Cracks after Compaction

3.3.2 Laboratory Samples

As mentioned before, the comparison between AASHTO T283, ASTM D4867, and MTO LS283 standard test methods requires a specific percentage of air voids content in each sample. Moreover, both AASHTO T283, and ASTM D4867 require that the degree of saturation ranges from 55% to 80%. To achieve these requirements, the relationship between air voids content and the number of blows were measured. In addition, the degree of saturation with different vacuum durations and compaction efforts were examined for the used mixes. Appendix 2 presents the calculations and the plotted diagrams for each mix.

3.3.3 Relationship between Air Voids and Number of Blows

Since ASTM D 4867 and AASHTO T283 both require 6-8% air voids while MTO LS 283 requires 8-12% air void, the objective of the section is to develop a relationship between the number of blows and the air voids in the specimen.

In order to develop these relationships, fifteen samples were prepared from each mix and then divided into six groups; each group represents a different number of blows (compaction effort). In addition, the dimensions and densities were measured and the contents of the air voids were calculated for each sample. The numbers of blows were set to five, 10, 20, 30, 40 and 50 blows for each group of samples. The density and air voids content was calculated for each group and the relationship was plotted for each mix. The plotted diagrams, which shown in Appendix 2, were used to estimate the required number of blows to achieve the specified air voids content for each mix and standard test method.

3.3.4 Relationship between the Degree of Saturation and Vacuum Duration for Different Compaction Levels

As mentioned before, some of the current standards require a certain degree of saturation for the laboratory prepared samples (55%-80% for ASTM D4867 and AASHTO T283).

To achieve the required degree of saturation at different compaction levels, the following steps were followed:

1. Fifteen samples were prepared from each mix. Samples were divided into five groups and each group had a different compaction effort (number of blows).
2. The samples were weighed in air (m_1).
3. Each set was subjected to a vacuum saturation for 10 min, 30 min and 60 min.
4. The samples were submerged in water and the submerged weight was recorded (m_2).
5. The samples were weighed again after the surface was dried (m_3).
6. Density as well as air voids were calculated using equations (3-2) and (3-3), while the degree of saturation (S_r) was calculated using the following equation;

Equation 3-5: Degree of Saturation

$$S_r = 100 * \left(\frac{m_3 - m_1}{m_1} \right)$$

where:

- S_r = the degree of saturation (%)
- m_1 = the weight of the sample in the air (g), and
- m_3 = the weight of the sample with a dry surface (g).

The details of the calculations and the plots are presented in Appendix 2.

3.3.5 Dimensions and Densities

For all the prepared samples, the dimensions and densities were measured according to ASTM D 3549-93a and ASTM D 2041-95 standards. The results for these measurements

are presented in Appendix 2. In addition, the physical properties of the extracted field cores are presented in the same appendix.

3.4 EVALUATION OF CURRENT LABORATORY TEST METHODS

The final stage of this phase presents a comparison between the results of moisture induced damage obtained by using AASHTO T 283, ASTM D4867, MTO LS 283 and PWGSC ASG 06 standard test methods. The objective of this stage is twofold: to check the correlation between field and laboratory performance, and to examine the ability of the selected standards in evaluating moisture induced damage of air field asphalt pavements.

3.4.1 Facilities Required for Testing Process

In order to achieve the required conditioning criteria for the above mentioned standards, the following facilities were used:

- Vacuum equipment: this equipment was used to achieve the required degree of saturation for any level of compaction.
- Curing room capable of keeping the temperature at 60° C while maintaining moving air (Air bath). This curing room was used during the process of the MTO LS 283 test.
- Refrigerator was imperative in order to achieve a freezing point at -16° C, which was an important step in the AASHTO T283 test.

- Warm water bath was needed since the required water temperature is 60° C. This equipment, CAN LAB B7005-3, was available made available by CLC and provided temperatures ranging from 0 to 100°C.
- Cooling water bath.

3.4.2 Marshall Immersion Test “PWGSC ASG 06”

For each mix, eight samples were prepared and divided into two groups with equal average density. The first group was an unconditioned group in which the samples were immersed in the warm water bath at $60^{\circ} \pm 1^{\circ}$ C for 30-40 minutes. The second group was conditioned and the samples were submerged in a warm water bath at $60^{\circ} \pm 1^{\circ}$ C for 24 hours. Finally, the mechanical properties for all samples were examined using Marshall Stability Test. The stability and flow were recorded for each sample. Appendix 3 presents the detailed calculations, while a summary of results for is presented in Table (3-3).

Table (3-3): Summary of the Results of the Marshall Stability for PWGSC Test Method

Mix	Stability (KN)							
	Conditioned				Dry			
Field Mix1	2.98	2.42	3.21	3.28	4.60	3.96	3.41	2.48
Field Mix2	2.00	1.60	2.02	1.84	1.90	1.68	2.33	1.86
Lab Mix1	14.60	12.01	9.90	11.42	16.10	12.21	15.18	13.36
Lab Mix2	18.87	13.92	16.99	15.88	18.22	15.84	16.29	19.46
Lab Mix3	15.62	14.21	12.76	13.06	16.25	15.78	12.57	14.44
Lab Mix4	14.40	12.30	12.70	14.90	16.40	15.00	13.80	12.80
Lab Mix5	13.90	14.00	13.00	13.90	15.90	14.00	15.30	14.80

3.4.3 Ontario Ministry of Transportation “MTO LS 283” Test

Six samples were prepared and divided into two groups having the specified limit of air voids content ranging from 8-12 %. The compacted specimens were cured with an air path at 60° C for 16-18 hours. In addition, the unconditioned samples were placed in a cooling water bath at $25 \pm 1^\circ$ C for one hour before the mechanical properties were examined using the Marshall Stability Test. The conditioned samples were subjected to a vacuum saturation for one hour at a residual pressure of 30mm Hg, followed by a warm water bath at $60^\circ \pm 1^\circ$ C for 24 hours and a cooling water bath for one hour before the conditioned and dry samples were tested using the Marshall Stability Test method. Table (3-4) is a summary of the results for the MTO .

Table (3-4): Summary of the Marshall Stability Results of the MTO LS 283

Mix	Stability (KN)					
	Conditioned			Dry		
Field Mix1	5.77	5.45	5.88	7.43	6.47	6.85
Field Mix2	7.31	6.69	10.74	15.57	14.82	23.23
Lab Mix1	13.76	14.36	14.11	13.85	13.18	15.86
Lab Mix2	16.59	16.65	17.36	22.58	22.84	25.20
Lab Mix3	16.34	17.06	16.35	19.83	17.55	21.62
Lab Mix4	28.50	27.60	26.60	39.20	39.30	38.70
Lab Mix5	23.30	22.60	21.60	29.00	29.70	28.70

3.4.4 ASTM D 4867 Test

Six samples were prepared and divided into two groups having approximately equal average air voids (7 ± 1 %). Before preparing the samples for this test, the mix was

placed in the oven for one to two hours at the compaction temperature. The unconditioned group was stored and was immersed into the water at room temperature for 20 minutes before it was subjected to the ITS test. The conditioned samples were partially saturated at 55-80% and were placed in the water bath at $60 \pm 1^\circ \text{C}$ for 24 hours, followed by a cooling water bath at $25 \pm 1^\circ \text{C}$ for one hour. A summary of the results is shown in Table (3-5).

Table (3-5): Summary of the Indirect Tensile Strength Test Method for ASTM D 4867

Mix	Ultimate Load at Failure (KN)					
	Conditioned			Dry		
Field Mix1	4.70	4.07	4.36	4.83	4.49	4.76
Field Mix2	2.08	2.38	3.06	3.35	3.69	4.77
Lab Mix1	5.57	5.56	4.98	7.23	7.09	7.91
Lab Mix2	4.00	4.84	4.91	5.23	7.79	7.79
Lab Mix3	5.80	6.13	5.96	10.04	8.55	6.44
Lab Mix4	8.04	8.41	7.10	13.23	11.06	11.70
Lab Mix5	7.15	6.58	6.48	8.37	8.51	8.13

3.4.5 AASHTO T283 Test

Six samples were prepared and divided into two groups having approximately equal average air voids ($7 \pm 1\%$). Before the samples were prepared, each mix was placed into the oven first for 2 hours at room temperature, then for 16 hours at 60°C , and finally for 2 hours at 135°C . Afterwards, each mix was raised to the compaction temperature. The unconditioned samples were stored at room temperature before the time of testing; whereas the conditioned samples were subjected to the vacuum saturation and were

immersed in the water bath at room temperature for 30 minutes. Then, the degree of saturation was calculated and the samples were frozen at -18°C for 16 hours and then thawed at 60°C for 24 hours. Finally, the samples were placed in the cooling water bath at 25°C for two hours before they were examined using the ITS test. The results of the tested samples (dry and conditioned) are presented in Table (3-6).

Table (3-6): Summary of the Indirect Tensile Strength Test Method for AASHTO T 283

Mix	Ultimate Load at Failure (KN)					
	Conditioned			Dry		
Field Mix1	4.77	3.46	3.95	5.34	4.71	4.89
Field Mix2	1.83	2.14	2.81	3.84	4.19	4.2
Lab Mix1	5.77	5.45	5.88	7.43	6.47	6.85
Lab Mix2	4.23	4.81	6.25	6.17	8.94	6.17
Lab Mix3	7.12	5.55	5.61	6.17	7.46	7.72
Lab Mix4	9.36	8.98	9.46	10.69	10.78	10.83
Lab Mix5	6.57	6.48	6.27	6.81	7.1	7.24

3.5 OBSERVATIONS AND ANALYSIS OF THE RESULTS

The Marshall Stability Ratio (MSR) was calculated using Equation 2.1 for both PWGSC and MTO while the TSR for each mix was calculated using Equation 2.3 for both ASTM and AASHTO. The calculations are presented in Tables (3-6) and (3-7). Table (3-6) shows the results for Mix 1 and Mix2 for the field and laboratory samples; while Table (3-7) presents the results of the calculations for all laboratory samples. In addition, the results are plotted in Figure (3-8) in order to compare field and laboratory

results for both Mix1 and Mix2. Finally, Figure (3-9) presents the comparison between different standard test methods for laboratory samples only.

Table (3-7): Summary of the Results of Field and Laboratory Samples

Test			Mix1	Mix2
PWGSC	Lab	*MSR	84.3	94.1
	Field	*MSR	82.3	95.9
MTO	Lab	*MSR	98.5	71.7
	Field	*MSR	64.5	46.1
ASTM	Lab	§TSR	74.3	70.3
	Field	§TSR	79.7	63.8
AASHTO	Lab	§TSR	79.7	71.07
	Field	§TSR	85.1	55.3

*MSR Marshall Stability Ratio
§TSR Tensile Strength Ratio

Figure (3-8): Comparison of Laboratory and Field Results

Table (3-8): Summary of the Results for Laboratory Samples

Test		Mix1	Mix2	Mix3	Mix4	Mix5
PWGSC	MSR	84.3	94.1	94.3	94	91
MTO	MSR	98.5	71.7	84.3	71	77
ASTM	TSR	74.3	70.3	72.3	65	81
AASHTO	TSR	79.7	71.07	76.1	86	91

Figure (3-9): Laboratory Samples Diagram

3.5.1 Observations

Based on the results listed in Tables (3-6), (3-7) and the plot of these results in Figures (3-8) and (3-9), as well as the test procedure for each method, the following points can be summarised:

- 1 The examined mixes in this research meet the required specifications (PWGSC ASG 06).
- 2 Sample preparation (air voids content) varies from one standard test to another. Based on the results, the effect of air voids content on stripping should be investigated.
- 3 Table (3-7) shows that the obtained failure rates for the field and laboratory samples are different. The discrepancy may be due to construction cracks as well as the air

voids content in the field sample. Therefore, it is recommended to investigate the effects of construction factors on stripping.

- 4 The process of sample conditioning is different from one standard test to another. Only some of the test methods require freezing and thawing durations, while all, require a warm water bath duration and/or cooling with different durations. Therefore, it is recommended to investigate the effect of the warm water bath and cooling water bath durations on the retain strength.
- 5 The examined standard test methods exemplified that the vacuum effect (degree of saturation) has a wide range and needs to be investigated in the next stage.
- 6 The mixes that were tested using PWGSC obtained a retained strength above the required 75% in order to pass any mix. More importantly, retained strength of Mix4, which is known to be susceptible to stripping, was 94%, which means that the PWGSC was not able to identify stripping in the Mix4. This finding may be the result of soaking the unconditioned samples in the warm water bath for 30 to 40 minutes.
- 7 The MTO did not identify the stripping for Mix4 since it has 71% of retained strength while it requires 70% to pass. In addition, the difference of the retained strength between laboratory and field samples was very high, ranging from 98.5% retained strength for lab samples to 64.5% for Mix1.
- 8 ASTM failed all the examined mixes, except Mix5, which means that it has a severe conditioning process.
- 9 The AASHTO passed the susceptible mix with 86% retained strength (Mix4), while it failed the non-susceptible mixes, including Mix2.

3.5.2 Statistical Analysis

The analysis of variance (ANOVA) was carried out to test the significance of the difference between the mean values of each standard test parameter for different mixes. In addition, a t-test was performed to evaluate the ability of each standard test method to identify the effect of sample conditioning. The null hypothesis of ANOVA was $H_0: \mu_{\text{Mix1}} = \mu_{\text{HMix2}} = \mu_{\text{Mix3}} = \mu_{\text{Mix4}} = \mu_{\text{Mix5}}$; where the μ 's are the mean values of each test parameter (ITS) for each mix types. The ANOVA was performed twice: first using the results of the unconditioned sample and secondly using the results of the conditioned samples.

As shown in the Tables (3-9) and (3-10) for the unconditioned and conditioned samples respectively, the evaluated standards yield a significant difference between the seven mixes (five laboratory, and two field) tested at a level of significance, $\alpha = 5\%$. The ANOVA results rejected the null hypothesis, which means that the examined test methods were able to differentiate between different mixes. Furthermore, the t-tests were carried out in order to examine the effect of the conditioning process on the load at failure. The null hypothesis of the t-test was assumed to be the case in which the mean of the conditioned and unconditioned parameter (indirect tensile strength or Marshall stability) are equal for each mix depending on the used standard test method. Before running the t-test, the variance of the two set of data was check and resulted in equal variance for all data, Appendix 3 has all the detailed calculations.

Assuming that the null hypothesis will be accepted if $\alpha > 0.05$; the results of the t-test, which are presented in Table (3-11), show that PWGSC accepts the null hypothesis

for six out of the seven examined mixes, which means that the PWGSC was not able to differentiate between the conditioned and uncontained samples. In other words, PWGSC results showed that the conditioning process did not significantly affect the load at failure.

The MTO failed to identify stripping in two out of the seven mixes, whereas the ASTM and AASHTO failed to identify stripping in three out of the seven mixes.

Table (3-9): ANOVA for Unconditioned Samples

		Sum of Squares	df	Mean Square	F	α
PWGSC	Between Groups	715.017	6	119.169	61.069	.000
	Within Groups	27.319	14	1.951		
	Total	742.336	20			
MTO	Between Groups	1956.278	6	326.046	74.949	.000
	Within Groups	60.903	14	4.350		
	Total	2017.181	20			
ASTM	Between Groups	127.327	6	21.221	19.862	.000
	Within Groups	14.958	14	1.068		
	Total	142.286	20			
AASHTO	Between Groups	80.303	6	13.384	27.511	.000
	Within Groups	6.811	14	.486		
	Total	87.113	20			

Table (3-10): ANOVA for Conditioned Samples

		Sum of Squares	df	Mean Square	F	α
PWGSC	Between Groups	551.123	6	91.854	95.636	.000
	Within Groups	13.446	14	.960		
	Total	564.570	20			
MTO	Between Groups	1041.007	6	173.501	176.359	.000
	Within Groups	13.773	14	.984		
	Total	1054.780	20			
ASTM	Between Groups	54.506	6	9.084	47.595	.000
	Within Groups	2.672	14	.191		
	Total	57.178	20			
AASHTO	Between Groups	84.517	6	14.086	36.521	.000
	Within Groups	5.400	14	.386		
	Total	89.917	20			

Table (3-11): Summary t-test for the examined standard test methods

Mix	PWGSC			MTO			ASTM			AASHTO		
	t	df	α	t	df	α	t	df	α	t	df	α
Field Mix1	1.307	6	0.239*	3.957	4	0.017	1.512	4	0.205*	2.162	4	0.097*
Field Mix2	0.460	6	0.662*	4.383	4	0.012	2.766	4	0.051*	5.814	4	0.004
Lab Mix1	1.696	6	0.141*	0.267	4	0.803*	6.382	4	0.003	3.957	4	0.017
Lab Mix2	0.776	6	0.467*	7.677	4	0.002	2.609	4	0.059*	1.993	4	0.117*
Lab Mix3	0.808	6	0.450*	2.566	4	0.062*	2.269	4	0.086*	1.457	4	0.219*
Lab Mix4	0.922	6	0.392*	19.853	4	Zero	5.510	4	0.005	9.879	4	0.001
Lab Mix5	2.793	6	0.031	11.528	4	Zero	6.770	4	0.002	3.943	4	0.017

* accept the null hypothesis.

3.6 REMARKS AND RECOMMENDATIONS

This phase of the research program presented the evaluation of the physical characteristics of the mixes that will be used during this and the next phases. In addition, it presented the preparation of the field and laboratory samples. The main objective of this phase was to assess the ability of the current standards to identify stripping in different mixes. Five standard mixes were tested in four different standard testing procedures resulting in four parameters per mix type for the dry samples and four parameters for the conditioned samples. The parameters were compared using the t-test to identify the potential of the examined standard test methods and to recognize the variability in performance using different mixes.

The ANOVA results showed that the current standards were able to identify the difference between the examined mixes for both dry and wet samples. However, when the t-test was performed to examine the ability of these standards to differentiate between the conditioned and unconditioned samples, the results showed that the four evaluated standard test methods failed to identify the difference in at least two out of the seven used mixes. Based on the literature review and the presented results for the first phase; it is possible to conclude that the performance of the current standards should be improved or replaced by developing new guidelines that may be used to identify the stripping. Therefore, it is recommended to investigate the following parameters in order to improve the performance of the developed guidelines:

- Construction effects (surface cracks and air voids content)

- **Environmental effects (freezing thaw cycles and degree of saturation)**
- **Test duration and conditioning (warm and cooling water bath).**

4 PARAMETRIC INVESTIGATION

4.1 INTRODUCTION

As outlined in Chapter 1, this chapter will present the details of phase 2 and phase 3 of the experimental program. Figure (4-1) shows the major phases of the research plan. The testing program carried out in Phase 1 included the preparation and evaluation of twenty-six asphalt specimens from various mixes using the current standard test methods. The outcome of Phase 1 and the literature review are used to carry out a parametric analysis in Phase 2. The parametric analysis will consist of an assessment of the effects of construction and environmental conditions and the impact of conditioning factors on the susceptibility of the mixes to stripping. As shown in Figure (4-2), six major variables will be considered for Phase 2.

With reference to construction factors, the effects of surface cracks and air voids content on stripping will be examined. The effects of surface cracks on moisture induced damage will be assessed using laboratory and field samples prepared from two different mixes. The evaluation of air voids content on the other hand will be performed using laboratory asphalt samples prepared from four different mixes. The assessment of these variables is intended to detect a relationship between air voids content and susceptibility to stripping, which could be used to determine the critical permeability limits in Phase 5 of the research plan. Moreover, an investigation of the effect of air voids content in conjunction with the warm water bath soaking temperature on the TSR will be part of this investigation.

Figure (4-1): Research Plan

Figure (4-2): Details of the Parametric Investigation

The evaluation of the conditioning factors will furthermore include the warm water bath duration and the cooling water bath duration. Six different durations and four mixes will be considered in order to investigate the cooling duration effect on the measured property. The evaluation of the effect of warm water bath durations will be carried out

using five different mixes and eight different durations. Laboratory prepared samples as well as field extracted cores, will be used in order to assure a better correlation between laboratory measurements and field performance. The tests will be performed under one set of conditioning procedures to ensure proper testing time suitable for the development of new test guidelines.

The environmental variables, which include the degree of saturation and the freezing thaw effect, will be carried out during phase 2. The degree of saturation is evaluated using two different mixes and six levels of degree of saturation. In addition, phase 2 will evaluate the effect of freeze/thaw cycles combined with the degree of saturation using four freezing periods ranging from 1 hour to a maximum of 24 hours. The results of these phases are expected to generate sufficient data and information in order to establish the guidelines needed for phase 3 of the research plan.

Phase 3 covers the examination of five different test methods used to measure the mechanical properties of the tested samples, representing the final step of the stripping evaluation. The five different test methods will be examined using different airfield and highway mixes in order to study their ability to evaluate the mechanical properties of the susceptible asphalt mixes. These tests include the Resilient Modulus, which is a dynamic test, whereas the static test methods include the Indirect Tensile, the Marshall test, the direct compression test method, and the shear strength test method. Figure (4-3) shows the schematic diagram of phase 3.

Figure (4-3): Details of the Experimental Program of Phase 3

In summary, this chapter will discuss the testing program and will exemplify the results of the parametric investigation that will be used for the development of guidelines for new standard test methods. First, construction effects, such as surface cracks and air voids content will be investigated. Second, conditioning effects, including warm and cold water baths and environmental factors, such as degree of saturation and freezing thaw cycles, will be analyzed. Finally, phase 3 will be presented, which investigates the suitable test method for the examination of mechanical properties of the tested samples. An introduction, testing procedures and results for each investigated parameter will be presented.

4.2 CONSTRUCTION FACTORS

4.2.1 Introduction

Pavement construction, specifically compaction, is one of the most crucial factors influencing performance with reference to moisture damage (Kandhal 1992, Terrel and Al-Swailmi 1993, and Mohamed et al. 1993). Different analyses have been reported to explain the influence of pavement compaction on stripping. Moreover, surface construction-induced cracks caused by compaction can create channels for surface water to permeate the pavement layer and initiate the stripping problem (Mohamed et al. 1993). Therefore, the presence of construction cracks can be detrimental to the pavement's stripping resistance.

It is well known that the objectives of compaction include the achievement of optimum density, the minimization of air voids content, and the reduction of permeability. In theory, good compaction should not be difficult, since the only requirements are the use of an appropriate compactor device and material that is in good condition.

Despite the fact that asphalt compaction has been recognized by many experts as one of the most important factors affecting asphalt pavement performance, the current compaction techniques are used without significant change or improvement for over eighty years. The compaction problems are frequently attributed to deficiencies in base stability, operator error, or the asphalt mix itself (Geller 1982). Other reports suggest that conventional steel rollers are to blame for construction cracks (Mostafa and Abd El Halim 2004, Abd El Halim et al. 1993, and 1994). In addition, it has been found that the Superpave mixtures add to the problem (Brown 1998).

The main objectives of this section are to compare current standards which used to evaluate stripping in order to assess the effect of surface cracks, and to quantify the effect of surface cracks on stripping evaluation. Moreover, the effect of air voids content on stripping will be evaluated and, critical air voids content that is suitable to identify stripping will be categorized. In addition, the critical air voids content will be used to determine the critical permeability limits that will be discussed during phase 5. Finally, the effect of the combination of air voids content and soaking temperature during the conditioning process will be investigated. In order to achieve the outlined objectives, the experimental program will be divided into two stages. The first stage compares different

standard test methods in order to evaluate construction cracks, while the second stage examines the effect of surface cracks direction relative to the loading direction during the measurements of the mechanical properties of the tested samples. Moreover the effects of different air voids content on stripping at constant soaking temperature will be investigated and followed with a discussion on the effects of changes in air voids content and soaking temperature.

4.2.2 Investigation of the Effect of Surface Cracks on TSR

The experimental program, as shown in Figure (4-4), consists of two main stages. The first stage evaluates the effects of surface cracks on the Tensile Strength Ratio (TSR) using four major standard test methods, including AASHTO T283, ASTM D4867, PWGSC "Marshall Immersing Test", and Ministry of Transportation Ontario (MTO) LS 283. As mentioned before, the selection of the first two standard test methods is based on the ranking among the other standard test methods, while MTO and PWGSC are selected to represent Canadian standard test methods. Based on the results of the first stage, the second stage aims to evaluate the effect of surface cracks direction on the mechanical properties of the tested samples. The two stages start with the detailed testing program, and followed by showing the results and observations.

Figure (4-4): Details of Investigating Surface Cracks Effect

4.2.3 Test Procedure and Results

- **Stage 1:**

The testing program, as shown in Figure (4-4), is divided into two main stages. Stage one makes use of fifty two field cores and twenty six laboratory samples for each mix in order to evaluate the effect of surface cracks on the TSR using the selected standard test methods. The height of twenty six field cores has been adjusted from 75 mm to 63.5 mm by cutting off the top part in order to remove the cracks. The other twenty-six field cores have been adjusted from the bottom. It should be noted that Mix1 and Mix2, both have been presented in chapter 3, were used throughout the course of this stage.

The evaluation of the effect of surface cracks was carried out using four standard test methods. It is important to mention that AASHTO 283, MTO LS 283, and ASTM D4867 require six samples each, while PWGSC ASG 06 requires eight samples. In addition, the standards vary with regards to conditioning procedures and mechanical testing properties. However, all standards were in agreement with respect to dividing the number of samples into two equal groups: the first group was tested unconditioned, while the second group was conditioned before testing. Details of the properties of the prepared samples are shown in Appendix 4.

After the samples were prepared, the second step entailed evaluating the susceptibility of each group of samples by applying the standard test methods. The procedures of these standards have been presented in the literature review, and have been used within the first phase of the research plan.

Table (4-1) presents the change in percentage of the TSR for each different standard test method, assuming that the reference samples are the cracked field cores. This means that the presented TSR values are the difference between laboratory and cracked field samples as well as the difference between the non-cracked versus cracked field samples.

Figures (4-5) and (4-6) show the measured TSR values for each standard test method. The results shown in Table (4-1) suggested that surface cracks could lead to large values of variance, which may lead to miss-interpretation of the results.

The result of the comparison between the four major standards shows that the hairline cracks reduce the TSR. The reduction ranges from 4.1 percent to 62.7 percent. It is imperative here to mention that the MTO test method failed to identify the effect of surface cracks for the comparison between the cracked and non-cracked field cores. Moreover, the range of the reduction of the TSR was 3.5% to 62.7% percent for mix2 and 7.9% to 30.1% for mix1, which represents a lack of consistency between and within each standard test method. In addition, the severe effect of the conditioning process in both ASTM and AASHTO standards might be one of the main reasons for the increased differences in the TSR values of laboratory prepared samples and field extracted cores. The differences in the reduction of the TSR from one standard test method to another leads to the second stage, which aims to identify the influence of surface cracks direction on the TSR.

Table (4-1): Summary of the Results of Surface Cracks Effects Using Different Standards

	Mix1			Mix2		
	Laboratory (26)	Field No cracks (26)	Field Cracks (26)	Laboratory (26)	Field No cracks (26)	Field Cracks (26)
PWGSC (8)	11.6	10.5	Reference	7.7	12.8	Reference
MTO (6)	16.6	-9.5	Reference	4.1	-12.0	Reference
ASTM (6)	4.3	7.9	Reference	62.7	47.7	Reference
AASHTO (6)	9.3	30.1	Reference	3.5	-6.9	Reference

Figure (4-5): Effect of the Surface Cracks on Tensile Strength Ratio (Mix1)

Figure (4-6): Effect of the Surface Cracks on Tensile Strength Ratio (Mix2)

As mentioned before, the objective of the second stage is to investigate the effect of surface cracks direction on the mechanical properties of the tested samples using the Indirect Tensile Strength (ITS) test method. In order to achieve this objective, eighteen field core samples and six laboratory samples were prepared for each mix. In addition, three different sample categories were prepared from each mix:

- The first category consisted of cracked field samples
- The second category entailed non-cracked field samples.
- The third and last category included laboratory samples.

The procedures to evaluate the effect of the surface cracks direction on the mechanical properties were as follows:

1. The height of the field cores was reduced from 75 mm to 63.5 mm by cutting the top part off the six field cores in order to remove the cracks, while the other twelve field cores were adjusted only from the bottom in order to leave the original cracks as is.
2. The cracked samples were divided into two equal groups (six cores each).
3. Each group was divided into two subgroups with three samples each. The cracked samples were loaded parallel or perpendicular to the loading direction. Figure (4-7) shows the scheme of the test showing the loading direction.

Figure (4-7): Measuring Indirect Tensile Strength (Al-Swailmi 2003)

4. The first group was tested dry at 25°C. Three samples were loaded parallel to the cracks direction using the ITS test and the rest of the samples were loaded perpendicular to the cracks.
5. The samples were then conditioned in warm water, and before being tested the samples were cooled for at 25°C.

6. The non-cracked field and laboratory samples were divided into two groups. One group was tested dry and the second was tested after conditioning.

The ITS values for cracked field cores are shown in Table (4-2), while Table (4-3) shows the TSR values for the same samples. The results show that the direction in which the field cracked cores are loaded is affecting its ITS. In addition, the conditioned samples have less TSR than dry samples.

In view of the fact that PWGSC ASG 06 accepts 75 percent retained TSR; it is obvious that the TSR of the laboratory and non-cracked field samples passes the required TSR value except the non-cracked field cores of Mix2. In addition, it is essential to note that all the cracked cores have a TSR of less than 75 percent.

Comparing the results of the non-cracked samples with the cracked ones showed that the difference in cracked and non-cracked field cores ranged from 6% to 14 %. When the laboratory samples were compared to the cracked field cores, the difference ranged from 14-24%. Hence, it is recommended to reduce the laboratory TSR by at least 10% while examining the susceptibility to moisture damage in the laboratory.

Judging from the results, the only standard test that might accept cracked field samples appears to be the MTO. However, as indicated in Tables (4-2) and (4-3), the comparison between the results of MTO and other standards shows that MTO results were not correlated to the results of the other standard test methods.

Table (4-2): Indirect Tensile Strength for the Second Stage (Cracked Field Cores)

Sample	Mix Type	Condition	Air Voids Content		Loading Direction	Indirect Tensile Strength	
			%	Average		Average (MPa)	% Change
29	Mix1	Dry	4.2	4.6	Parallel	0.9473	4.4
31			5.3				
32			4.2				
33	Mix1	Dry	4.2	4.8	Perpendicular	0.9887	
35			5.6				
35			4.6				
19	Mix2	Dry	8.3	8.6	Parallel	0.6397	8.5
20			8.8				
21			8.6				
22	Mix2	Dry	8.2	8.1	Perpendicular	0.6941	
23			8.0				
24			8.1				
1	Mix1	Conditioned	5.3	4.7	Parallel	0.6534	9.0
2			4.2				
3			4.7				
4	Mix1	Conditioned	3.9	4.4	Perpendicular	0.7122	
5			4.5				
6			4.8				
31	Mix2	Conditioned	10.0	9.6	Parallel	0.3229	38.0
32			11.0				
33			7.8				
16	Mix2	Conditioned	7.0	8.5	Perpendicular	0.4455	
17			7.8				
18			10.7				

Table (4-3): Summary of the Tensile Strength Ratio (TSR).

Mix	Air voids	Direction of Loading	TSR %	Change of TSR
Mix1	4.65	Parallel	69.0	4.3
Mix1	4.60	Perpendicular	72.0	
Mix2	9.10	Parallel	50.5	27.1
Mix2	8.30	Perpendicular	64.2	

To conclude, the observations showed that surface cracks affect the evaluation of moisture sensitivity, which could be the main reason for the lack of a correlation between samples tested in the laboratory and field performance. Therefore, a further analysis of the effect of surface cracks is recommended.

Table (4-4): Summary of the Tensile Strength Ratio (TSR) for the Second Stage

Sample #	Mix Type	Condition	Air Voids Content		Indirect Tensile Strength	
			Percentage	Average	Average (MPa)	TSR
1	Lab Mix1	Dry	3.6	3.4	1.92	85
2			3.2			
3			3.5			
4	Lab Mix1	Condition	3.9	3.5	1.64	
5			3.2			
6			3.5			
7	Lab Mix2	Dry	3.2	3.3	1.66	81
8			3.1			
9			3.5			
10	Lab Mix2	Condition	3.5	3.5	1.34	
11			3.6			
12			3.5			
1	Field Mix1	Dry	5.2	5.4	1.11	77
2			5.4			
3			5.7			
4	Field Mix1	Condition	4.9	5.4	0.85	
5			5.5			
6			5.8			
7	Field Mix2	Dry	6.6	6.0	0.82	71
8			6.2			
9			5.3			
10	Field Mix2	Condition	6.1	6.1	0.58	
11			5.4			
12			6.8			

4.2.4 Testing Program for Air Voids Content

Density or in-place air voids are important components of a properly designed and constructed asphalt pavement. Selecting the proper compaction level during the mix design phase is critical for proper pavement performance. The differences between investigated standard test methods (Phase1) showed that it is important to investigate the relationship between the air voids content and stripping represented by the TSR (i.e. PWGSC requires 3% while MTO requires 8 to 12%). As has been previously recognized, the produced air voids content is higher than that required by the mix design (6 to 8%), which is due to field compaction. Therefore, the objective of this investigation is to determine the suitable air voids content during the preparation of the laboratory samples, which would be used to identify stripping.

This investigation consists of two stages. The first stage examines the effect of a change in air voids content with a soaking temperature of 60 °C, while the second stage investigates the effect of a change in the soaking temperature and the air voids content on the TSR.

The test program for the investigation of the effect of the air voids content on the TSR is shown in Figure (4-8). The testing program for both stages started with a preparation of the samples and was followed by the conditioning procedure. Finally, the mechanical properties for the conditioned and unconditioned samples were tested. For the first stage of the testing program the procedure went as follows:

- 30 samples were prepared from each mix (Mix1, Mix3, Mix4, and Mix5) and subsequently divided into five groups.

- Each group was divided into two subset groups with each group having an approximately equal amount of air voids content. The first subset was tested dry, while the second group was conditioned before testing using the ITS test. Dimensions and densities were then measured.
- The conditioning process was the same for all conditioned groups (soaking in warm water at 60° C, followed by soaking in a cooling water bath at 25° C for an equal period of time).

The mechanical properties were measured using the ITS test and the TSR was calculated and presented in Table (4-5).

Table (4-5): Summary of then TSR values at Different Air Voids Content for 60° C

Mix4		Mix5		Mix3		Mix1	
Air Voids	TSR	Air Voids	TSR	Air Voids	TSR	Air Voids	TSR
4.9	92.2	3.6	87.6	1.9	90.4	1.8	88.7
6.3	90.3	4.4	89.0	3.5	90.7	2.2	87.9
8.9	86.4	8.3	86.1	7.2	88.5	4.2	85.3
12.8	75.7	10.4	85.5	9.4	89.8	6.8	80.3
16.0	73.15	12.9	82.1	12.3	85.5	9.8	78.4

Figure (4-8): Detailed Experimental Program for the Construction Effect

The second stage of the experimental program used Mix4 and Mix5 and three different soaking temperatures ranging from 60° C, 70° C to 80° C were examined, However, since the first stage already covered the soaking temperature of 60° C, this stage will cover the soaking temperatures of 70 °C and 80 °C respectively:

- One hundred and twenty samples were prepared representing two mixes of 60 °C each for a final count of thirty samples for each soaking temperature of 70 °C and 80 °C.
- The thirty samples were divided into five equal groups and each group was divided into two subsets with an approximate equal average density (air voids content).
- Dimensions and densities were measured before testing.
- The first subset was tested dry, while the second subset was conditioned before testing.
- The conditioning process included soaks in a warm water bath at 70° C or 80° C, and was followed by soaks in a cooling water bath at 25 °C. all groups were subjected to the same process of conditioning.
- The mechanical properties of the samples were tested using the ITS test. The TSR was calculated for each sample group and is presented in Table (4-6). The details of the calculations are presented in Appendix 4.

Table (4-6): Summary of the TSR for every value of Air Voids Content for stage 2

Mix-4						Mix-5					
60° C		70° C		80° C		60° C		70° C		80° C	
AV*	TSR§	AV*	TSR§	AV*	TSR§	AV*	TSR§	AV*	TSR§	AV*	TSR§
4.9	92.2	5.05	78.2	5.10	55	3.6	87.6	7.35	73	5	50.5
6.3	90.3	8.15	69.7	7.50	15	4.4	89.0	7.65	69.9	6.2	30
8.9	86.4	11.85	43.3	11.24	0	8.3	86.1	10.32	59.3	9.3	0
12.8	75.7	15.50	55	14.56	0	10.4	85.5	12.2	53.4	11.3	0
16.0	73.15	21.15	61.7	20.80	0	12.9	82.1	15.7	58.9	16	0

*AV: air voids content

§ TSR: Tensile Strength Ratio

4.3 *CONDITIONING FACTORS*

4.3.1 Introduction

It is known that the degree of susceptibility to the moisture-induced damage is determined by preparing a set of laboratory-compacted specimens conforming to the job-mix formula. The specimen are compacted to specific air voids content, and each set of samples is divided into two subsets (groups) of approximately equal void content. Whereas one subset is maintained dry (“unconditioned”) and used as a control group, the other subset is treated (“conditioned”). The tensile strength of each subset is determined using the tensile strength test. In addition, the potential for moisture-induced damage is measured by calculating the ratio of the tensile strength of the wet subset to that of the control subset. Based on the literature review, the conditioning process may include one or more of the following steps:

1. Soaking the samples in a 60°C water bath for a certain duration,
2. Cooling the samples in a water bath at 25°C for a certain duration
3. Vacuuming the samples to a certain degree of saturation
4. Freezing thaw cycles
5. Measuring the mechanical properties for the conditioned and the control group.

The literature review showed that the standards differ in their conditioning procedures for samples and the test may take one to three days in order to be completed. The objectives of this part of the research plan are to identify the optimum warming water bath duration and temperature as well as the cooling water bath duration without compromising the test results. This section starts with an investigation of the effect of the warm water bath duration on the TSR. Then, the effects of changing the soaking temperature will be measured, which will be followed by an examination of the effect of the cooling water bath duration on the TSR.

4.3.2 Testing Program

4.3.2.1 Investigating the Effect of Warm Water Bath Duration

During the evaluation of the current standard test methods, the results showed a lack of correlation between the laboratory-manufactured samples and field extracted cores. In addition, the PWGSC soaks the unconditioned samples for 30 to 40 minutes while the rest of the standards only soak the conditioned samples for twenty-four hours at

60° C. Therefore, the samples here are soaked in a warm water bath in order to simulate the field effect.

To investigate the effect of the warm water bath duration on stripping $(TSR)_w$, five mixes were used. Twenty-four samples were prepared from each mix. The following steps were followed to investigate the effect of the warm water bath duration:

1. Five mixes and twenty-four samples were prepared from each mix.
2. The samples for each mix were divided into eight groups.
3. All groups were soaked into the warm water bath for different durations (0.25, 0.5, 1.0, 2.0, 4.0, 6.0, 8.0, and 24 hours). Figure (4-9) shows the device that is used to soak the samples in a warm water bath, adjusted at 60 °C.
4. The group with a soaking duration of 0.25 hour was selected to be the control group.
5. The mechanical properties of the samples were examined using the ITS test.
6. The $(TSR)_w$ for each group of samples was calculated as the ratio between its ITS and the ITS of the control group.
7. The percentage of change of $(TSR)_w$ was calculated as the difference between the $(TSR)_w$ for any set of samples with a known soaking duration and the $(TSR)_w$ of the control group.

Figure (4-9): Warm Water Bath Soaking Device

4.3.2.2 Results and Observations

Table (4-7) shows a summary of the ITS test results for the five tested mixes, while Table (4-8) shows the $(TSR)_w$ and Table (4-9) presents the percentage of the change of the $(TSR)_w$ for different soaking durations. A careful observation of the results led to the conclusion that when the samples were immersed for half an hour, a minimum loss of 30 % tensile strength occurred (except for mix-1, where the loss was 14 %) . In addition, the average loss of the $(TSR)_w$ for a two hour soaking duration was 65 %. On the other hand, the reduction of the $(TSR)_w$ for soaking periods ranging from eight to twenty four hours, was less than 5%. Interestingly enough, in some cases the $(TSR)_w$ was higher for the 24 hour soaking duration than for the 8 hour soaking duration.

As is commonly known, the PWGSC test procedure requires the unconditioned samples to be immersed in a warm water bath for 30-40min, which (based on the current results) reduces the tensile strength of the examined samples to a minimum of 30%, compared to the control group. Given the results, it is recommended that the soaking of the unconditioned samples in the warm water bath for the PWGSC standard test method to be eliminated, and to minimize the warm water bath duration for the conditioned samples.

Table (4-7): Indirect Tensile Strength (ITS) Value for Soaking Duration

Duration Hours	ITS (MPa)				
	Lab Mix1	Lab Mix4	Lab Mix5	Field Mix2	Field Mix1
0.25	0.45	0.38	0.35	0.15	0.17
0.5	0.38	0.26	0.25	0.09	0.10
1	0.30	0.22	0.20	0.07	0.08
2	0.25	0.21	0.15	0.04	0.07
4	0.25	0.19	0.14	0.05	0.05
6	0.24	0.16	0.11	0.05	0.04
8	0.21	0.14	0.11	0.02	0.04
24	0.19	0.13	0.10	0.02	0.04

Table (4-8): Tensile Strength Ratio (TSR)_w value for soaking duration

Duration Hours	(TSR) _w (percentage)				
	Lab Mix1	Lab Mix4	Lab Mix5	Field Mix2	Field Mix1
0.25	100	100	100	100	100
0.5	86	68	71	61	58
1	66	58	56	48	48
2	57	56	41	30	41
4	57	49	41	36	29
6	54	43	32	31	26
8	48	36	32	14	22
24	43	35	27	12	22

Table (4-9): Percentage of Change of (TSR) for different soaking duration

Duration Hour	Percentage Change of (TSR) _w				
	Lab Mix1	Lab Mix4	Lab Mix5	Field Mix2	Field Mix1
0.25	Zero	Zero	Zero	Zero	Zero
0.5	-14	-32	-29	-39	-42
1	-34	-42	-44	-52	-52
2	-43	-44	-59	-70	-59
4	-43	-51	-59	-64	-71
6	-46	-57	-68	-69	-74
8	-52	-64	-68	-86	-78
24	-57	-65	-73	-88	-78

4.3.3 Testing Program of Cooling Water Bath

4.3.3.1 Introduction and procedure

During the evaluation procedure of moisture induced damage using ASSHTO, ASTM, MTO or PWGSC standards, the cooling duration ranged from zero for the PWGSC test method to 120 minutes for the AASHTO T283 test method. As a result of this variation of the cooling duration, this investigation will examine the effect of the cooling duration on the TSR.

To evaluate the cooling temperature effect, four mixes were examined, including Mix1, Mix2, Mix6, and Mix7. Fifteen samples were prepared in the laboratory from each mix (Mix1, Mix6, and Mix7). Moreover, fifteen cores were extracted from the field from Mix1, and Mix2. The fifteen samples for each mix were divided into five groups of approximately equal average density.

During this investigation, all the samples were submerged in the warm water bath for six hours at 60° C and then placed in the cooling water bath for different durations

(15, 30, 45, 60, 120, and 180 min). The potential for susceptibility to moisture-induced damage was examined using the ITS test and the ultimate load and corresponding displacement was recorded. The sample with a 15 minute cooling duration was designated to be the control group. The Indirect Tensile strength (ITS) was calculated and the Tensile Strength Ratio (TSR)_c considered as the ratio between the ITS of any group and the ITS of the control group.

4.3.3.2 Results and Observations

Table (4-10) shows the average ITS values, while Table (4-11) presents the average (TSR)_c for each group. Based on the results, the following observations can be made:

1. The ITS values for laboratory manufactured samples are higher than for field extracted cores, which could be due to surface cracks, and air voids content.
2. The ITS and the cooling duration are directly proportional. However, it seems that after one hour of cooling, the samples retain most of their strength.
3. The rate of change of the ITS and/or the (TSR)_c may offer an insight into how the cooling duration affects the tensile strength of the tested samples.

Table (4-10): Summary of the ITS Results of the Cooling Duration

Duration	Lab Mix1	Field Mix1	Field Mix2	Lab Mix 6	Lab Mix 7
Minutes	ITS (Mpa)				
15	0.99	0.07	0.3	0.53	0.82
30	1.03	0.08	0.35	0.56	1.04
60	1.08	0.11	0.35	0.83	1.17
120	1.14	0.11	0.39	0.91	1.2
180	1.21	0.14	0.29	0.83	1.11

Table (4-11): Summary of the (TSR)_c Results of the Cooling Duration

Duration	Lab Mix1	Field Mix1	Field Mix2	Lab Mix 6	Lab Mix 7	Average percentage
Minutes	Percentage					
15	100	100	100	100	100	100
30	104	114	117	106	127	113
60	109	157	117	157	143	136
120	115	157	130	172	146	144
180	122	200	97	157	135	142

4.4 ENVIRONMENTAL INVESTIGATION

4.4.1 Introduction

As has been discussed in the literature review, freezing thaw cycles may influence the TSR due to the moisture effect on the adhesion between aggregate and binder. The water may originate either from the surface or from the bottom of the asphalt layer via the capillary. The objective of this section is to evaluate the effect of freeze thaw and saturation level individually, and to combine both factors in order to assess their effects on the stripping of asphalt pavements.

In order to evaluate the effects of environmental conditions on stripping; this investigation is divided into three stages as shown in Figure (4-10). Stage 1 investigates the effect of the degree of saturation, whereas Stage 2 studies the effect of freezing thaw. Finally, Stage 3 concludes the investigation with an assessment of both factors (saturation and freezing thaw) in conjunction.

Figure (4-10): Detailed Experimental Program for Environmental Effect on Stripping

4.4.2 Investigating the Effect of the Degree of Saturation (Stage 1)

In order to study the effect of the degree of saturation on the (TSR) in the first stage, Mix 1 was considered and eighteen samples were prepared in the laboratory with the use of the Marshall Compactor. The prepared samples were divided into six groups with approximate equal average density. The vacuum duration ranged from zero minute for the control group to 180 minutes. The 180 minute duration was selected to ensure that the saturation level is at 100%. The incremental durations of vacuum saturation were selected to be at 0, 30, 45, 60, 120, and 180 minutes respectively. Figure (4-11) shows the device that was used to vacuum the samples.

The results of this stage are shown in Table (4-12), which moreover includes the TSR for different saturation levels based on the vacuum duration. The results of this first stage are plotted in Figure (4-12), which illustrated that the degree of saturation has a small effect on the TSR if the degree of saturation is less than 90 %. As the degree of saturation increases, the TSR decreases. However, the drop in the TSR was obvious after a 90% degree of saturation was achieved. The detailed calculations are shown in Appendix 4.

Figure (4-11): Vacuum Saturation Facility

Table (4-12): Summary of the Results of the Vacuum Duration Effect on TSR for Mix1 (Stage1).

Vacuum Duration (hr's)	0	0.5	0.75	1.0	2.0	3.0
Percentage of Saturation	0	56	63	90	96	97
Retained Strength (TSR) %	100	100	90.8	90.6	71.6	73.3

Figure (4-12): Effect of Degree of Saturation on the TSR

4.4.3 Investigating the Effect of Freeze Thaw Cycles (Stage 2)

Environmental conditions, such as the freezing thaw effect, have been discussed in many publications (Hassan et al. 2002). Although there is little agreement on the effects of freezing thaw cycles, the literature agrees that it may be a crucial parameter affecting moisture induced damage evaluation. Therefore, to investigate freezing thaw cycles, two mixes were used and 15 samples were prepared in the laboratory from each mix. The samples were divided into five groups with an approximate equal average density.

Figure (4-13): Samples During Freezing

The test proceeded as follows:

- Dimensions and densities were measured for all samples.
- Freezing durations varied for different groups (zero, one, two, three, sixteen, and twenty-four hours). Figure (4-13) shows two groups of samples during the freezing stage.
- All groups were soaked in a warm water bath for the duration of six hours
- All groups were soaked in a cooling water bath for the duration of one hour.
- The mechanical properties were tested for all samples with the help of the ITS test.
- The load at failure was recorded for each sample, and the average ITS was calculated for each group.

- The load ratio was calculated for each group of samples. Assuming that the control group is represented by the samples without freezing duration. Table (4-13) shows the summary of these values while Figure (4-14) presenting these results.

Table (4-13): Summary of the Results of the Freezing Effect (Stage 2)

Freezing Duration	Lab Mix1		Field Mix2	
	Average Load at Failure (KN)	Load Ratio	Average Load at Failure (KN)	Load Ratio
0	550.6	100.0	127.4	100.0
2	725.3	131.7	135.3	106.2
4	570.5	103.6	146.6	115.1
16	537.0	97.5	123.5	96.9
24	748.9	136.0	138.6	108.8

Figure (4-14): Freezing Duration versus the Load Ratio at Failure.

The results of the second stage illustrate that the effect of the freezing duration on the TSR does not lead to a trend. Nevertheless, it still remains imperative to investigate the freezing effect with partially saturated samples ($60\pm 5\%$), which will be discussed below.

4.4.4 Investigating the Effect of Degree of Saturation and Freeze Thaw on TSR (Stage 3)

For the investigation of both environmental factors, including the degree of saturation and the freezing thaw cycles, the samples were prepared from Mix1, Mix2, Mix6 and Mix7. Eighteen samples were prepared from each mix, except Mix 2, which only yielded 9 samples. The eighteen samples were divided into six groups with approximate equal average density. Dimensions and densities were measured and presented in Appendix 4. The experimental program was completed as follows:

- All samples were vacuumed for a period pending on the results from stage1 in order to ensure that the degree of saturation is not less than 65%.
- All samples were weighed to calculate the degree of saturation.
- All samples were placed in the freezer for different durations, as illustrated in Figure (4-13).
- All samples were removed from a freezer and placed in the warm water bath for a period of six hours.

- All the samples were placed in a cooling water bath for one hour.
- The mechanical properties for all samples were tested using the ITS test. The ultimate load and corresponding displacement was recorded.
- The TSR for each sample was calculated and presented in Table (4-14).

Table (4-14): Summary of the Results of the Effect of Freezing Thaw on TSR

Freezing Duration (Hour)	Field Mix2		Lab Mix1		Lab Mix6		Lab Mix7		Average	
	%Sr*	TSR	%Sr*	TSR	%Sr*	TSR	%Sr*	TSR	%Sr*	TSR
0	0	100	0	100	0	100	0	100	0	100
2	67	50	83	51	75	60	55	57	70	55
4	71	77	88	47	58	92	53	51	67	67
16	68	104	87	72	67	89	72	42	73	77
24			80	72	82	135	62	135	74	82
48			66	74	67	68	72	68	68	61

*Sr Degree of Saturation

The results show no clear relationship between the freezing thaw cycles and the TSR. However, the analysis will be continued in chapter five, where the results will be examined in a statistical manner.

4.5 MECHANICAL PROPERTIES INVESTIGATION

4.5.1 Introduction

Most asphalt pavements are designed and built to provide service life ranging from 15 to 20 years. However, this design objective is rarely met, due to the uncertainty of many design and construction variables. Over the past fifty years, deterioration of asphalt pavements has been identified to be the result of one or more of the following major distress modes: (1) surface cracking, (2) surface rutting and (3) stripping. One of the most acute problems associated with asphalt mix design, is the failure to predict the long-term performance, which results in an increase of road rehabilitation costs. One of the main challenges pavement researchers and engineers face is the establishment of a quality control test with which the long-term performance of newly laid asphalt mixes could be predicted.

Currently, the pavement industry invests a great deal of money and time to improve existing asphalt mixes in order to develop new and engineered asphalt binders, to utilize new materials and applications, and to establish new research efforts. While most of these attempts try to improve the properties of the asphalt materials based on laboratory results, field performance of asphalt roads utilizing these developed solutions has been noted to be less than acceptable. With reference to moisture damage for example, recent observations have led to the conclusion that in spite of the work expended to predict the long-term performance of pavements; the incidence of moisture-induced damage has not been decreasing but has rather been increasing. Recent research has tried to remedy the

decrease in reliability by pointing out the importance of adopting shear strength and/or shear modulus asphalt mixes as a more reliable indicator of the behaviour and long-term performance of asphalt mixes (Lai 1986). Clearly however, this suggested approach is loaded with a number of problems for the asphalt designers as well as for the pavement engineers.

Given the above mentioned challenges, Phase 3 will study laboratory testing methods for asphalt concrete pavements and will discuss the relationship between testing methods and the pavement's long-term performance. More importantly, this stage will try to identify tests that may offer reliable laboratory results with reference to stripping prediction.

In this phase, different test methods, including the shear strength test, the Resilient modulus, the direct compression test, the ITS and the Marshall Stability test were examined. Figure (4-3) presents the details of the experimental program. The test methods were selected to represent the major types of asphalt pavement distresses; whereas the shear strength test and the shear modulus test were chosen to represent rutting, the resilient modulus, indirect tensile, and Marshall stability test were selected to represent tension cracks.

In addition, the loading criteria for airfield pavements have both, dynamic and static types. Therefore, the selected test methods cover both types of loading: the resilient modulus is a dynamic test while the others are static tests.

This phase furthermore provides a description of the laboratory testing methods, which is followed by an outline of the testing program. Finally, the results are analyzed and the findings are summarized.

4.5.2 Laboratory Testing Methods

Various laboratory testing methods have been developed for pavement designers and researchers in order to assess the mechanical properties of asphalt concrete mixes. However, due to the scope of this phase, only four test methods will be studied. These four tests are:

4.5.2.1 Indirect Tensile Strength Test Method (ITS)

The indirect tensile strength test is a widely popular testing procedure. In the ITS test, the load is applied to a core sample as compression along one diameter as shown in Figure (4-15), thus producing tensile stresses along the perpendicular diameter. The sample is loaded until failure and the peak load is translated into the sample's indirect tensile strength (ITS) as follows:

Equation 4-1: Indirect Tensile Strength

$$ITS = \frac{2P}{\pi t D}$$

where:

P = the applied load (N),

t = sample thickness (mm), and

D = sample diameter (mm).

Because the tested sample fails due to tensile stresses, the test is believed to simulate the main failure mode of asphalt concrete pavements; namely cracking. Therefore, the test is believed to be a good indicator of the pavement's long-term performance and to be sufficiently accurate for routine quality control use. The Tensile Strength Ratio (TSR) was calculated as the ratio between average ITS for the wet "conditioned" samples divided by the average ITS for the dry "unconditioned" samples.

Equation 4-2: Tensile Strength Ratio

$$TSR = \frac{AverageITS_{wet}}{AverageITS_{dry}}$$

where:

Average ITS_{Dry} = the average ITS of the samples tested in an unconditioned state

Average ITS_{wet} = the average ITS of the samples tested in a conditioned state

Figure (4-15): The Indirect Tensile Strength Test Device

4.5.2.2 Resilient Modulus Test Method (M_R)

The main input to describe a pavement layer in most design models is the layer's elastic modulus. Therefore, in spite of the simplicity of the ITS test, the elastic modulus of the asphalt concrete pavement should be a more accurate indicator of the pavement's performance. However, because of the generally in-elastic behaviour of asphalt concrete pavements, the traditional initial modulus of elasticity based on a simple stress-strain curve has been deemed inaccurate. In recent years, the asphalt concrete pavement community has accepted a new replacement for the initial modulus of elasticity; namely the resilient modulus (M_R). In addition, because the test is non-destructive, the test has the ability to monitor the performance of the same samples during the progress of another testing procedure (Brown et al 1991).

The testing procedure for M_R has been standardized as ASTM D 4123 and AASHTO T 274. In either procedure, core specimens are loaded with a cyclic indirect tensile stress corresponding to 10 to 50% of the ITS. The main premise of this test is that if a pavement specimen is loaded with a relatively small load for a large number of cycles, plastic deformations will accumulate during the early cycles and only elastic deformations will be recorded later on (Brown et al 1991). To determine M_R , core samples are loaded using a diametrical compressive load. Both, the horizontal and vertical displacements are recorded during the loading cycles, Figure (4-16), and M_R (Mpa) can then be calculated as follows:

Equation 4-3: Poisson's ratio

$$\nu_R = \frac{3.59 \Delta H_T}{\Delta V_T} - 0.27$$

Equation 4-4: Resilient Modulus

$$M_R = \frac{P (\nu_R + 0.27)}{t \Delta H_T}$$

where:

P = maximum applied load (N),

ν_R = Poisson's ratio,

t = sample thickness (mm),

ΔH_T = total recoverable horizontal deformation (mm), and

ΔV_T = total recoverable vertical deformation (mm).

The Resilient Modulus Ratio (M_{RR}), which would be used to evaluate the asphalt mixes susceptibility to stripping, was calculated using the following equation:

Equation 4-5: Resilient Modulus Ratio

$$M_{RR} = \frac{\text{Average } M_{R \text{ wet}}}{\text{Average } M_{R \text{ Dry}}}$$

where:

Average $M_{R \text{ Dry}}$ = the average of the M_R of the samples that tested unconditioned,

Average $M_{R \text{ wet}}$ = the average of the M_R of the samples that tested conditioned

Figure (4-16): Resilient Modulus Test Device

4.5.2.3 Marshall Stability Test Method (MS)

The Marshall Stability test is a well-known test in the asphalt industry. ASTM D1559-89 explains the test procedure and gives full details for the required equipment. Moreover, the MTO and PWGSC adapted this test to examine the mechanical prosperities during the stripping evaluation process.

The main purpose of this test is to measure the stability and flow of the manufactured asphalt mixes (samples). The stability is defined as the maximum (ultimate) load that can be sustained by the sample (lb. or N), while the flow is measured using the attached flowmeter (0.01-inch or mm). The facility is connected to a data

acquisition system capable of collecting all the required data. Once these data are recorded, the Marshall Strength Ratio (MSR) is calculated using the following equation:

Equation 4-6: Marshall Strength Ratio

$$MSR = \frac{AverageMS_{wet}}{AverageMS_{Dry}}$$

where:

Average MS_{Dry} = the average of Marshall Stability (MS) for the samples that tested dry,

Average MS_{wet} = the average of Marshall Stability (MS) for the samples that tested wet.

4.5.2.4 Shear Strength Test Method (SS)

Shear strength and shear modulus of asphalt concrete pavements have recently received much attention as a fundamental property that can be related to the pavement's long-term performance, especially for rutting resistance. The main premise of using the shear strength and shear modulus as predictors of the rutting performance is that most of the rutting takes place in the top asphalt concrete layer due to shear flow. The Strategic Highway Research Program (SHRP) has therefore adopted shear strength to predict the long-term rutting resistance (Lai 1986). However, both the Superpave Shear Tester and the Field Shear Test developed by SHRP utilize a direct shear stress, which results in large stress concentration, especially on a ductile material such as asphalt concrete pavements. An alternative procedure has been developed at Carleton University utilizing

a torque applied to a core sample, so that the sample is subjected to pure shear stress (Goodman et al 2000).

The shear strength testing utilizes a core sample glued to two steel plates on both sides of the sample. A torque is then applied until failure as shown in Figure (4-17), and the maximum torque and angle of the twist can be used to determine the sample's shear strength (SS, Mpa) and shear modulus (G, Mpa) as follows:

Equation 4-7: Shear Strength

$$SS = \frac{T R}{J}$$

Equation 4-8: Shear Modulus

$$G = \frac{T L}{\theta J}$$

where:

T = maximum torque (N.mm),

J = polar moment of inertia (mm^4) = $\pi R^4/2$,

R = sample radius (mm), and

θ = angle of twist (rad).

Finally, the Shear Strength Ration (SSR) and Shear Strength Modulus (SMR) were calculated using the following equations:

Equation 4-9: Shear Strength Ration

$$SSR = \frac{AverageSS_{wet}}{AverageSS_{dry}}$$

Equation 4-10: Shear Strength Modulus

$$SMR = \frac{AverageSM_{wet}}{AverageSM_{dry}}$$

where:

SSR = the Shear Strength Ratio (percentage),

Average SS_{Dry} = the average of the SS of the samples that tested unconditioned,

Average SS_{wet} = the average of the SS of the samples that tested conditioned,

SMR = the Shear Modulus Ratio (percentage),

Average SM_{Dry} = the average of the SM of the samples that tested unconditioned,

Average SM_{wet} = the average of the SM of the samples that tested conditioned,

Figure (4-17): Shear Strength Test Device

4.5.2.5 Direct Compression Test Method (CS)

The Direct Compression test is a widely popular testing procedure used to examine the compression strength of the reinforced concrete. However, none of the current standard test methods used to detect moisture induced damage makes use of this test.

In the CS test, the load is applied to a core sample as compression along one axis and the sample is loaded until failure; the peak load and the corresponding displacements at failure are recorded. The ultimate load at failure was used to calculate the compression stress at failure as follows:

Equation 4-11: Direct Compression

$$CS = \frac{4P}{\pi D^2}$$

where:

P = the applied load at failure (N),

D = sample diameter (mm).

Because the tested sample fails due to compressive stresses, the test is believed to simulate the main failure mode of asphalt concrete pavements, which appears as a rut. Therefore, the test might be a good indicator of the pavement's long-term performance and could be correlated to field performance. Furthermore, the Compression Strength Ratio (CSR) was calculated for all groups using the following equation:

Equation 4-12: Compression Strength Ratio

$$CSR = \frac{AverageCS_{wet}}{AverageCS_{Dry}}$$

where:

Average CS_{Dry} = the average of the CS of the samples that tested unconditioned,

Average CS_{wet} = the average of the CS of the samples that tested conditioned

4.5.3 Testing Program

- To achieve the aforementioned objectives, an experimental investigation was designed to compare the results of the testing methods of five mixes (Mix1, Mix4, Mix5, Mix6, and Mix7).

- To allow a minimum of six samples per mix type per test method, a minimum of twenty-four specimens were required for each mix type. For each mix, the samples were divided into four groups. Each group was divided into two subsets; one was tested dry while the second one was tested after conditioning.
 - The first group was tested for ITS. The load was applied at a 50 mm/min rate, and a 19-mm strip was used to transmit the load from the loading plates to the sample.
 - The second group was tested for Marshall Stability.
 - The third group was tested first for M_R (non-destructive test) and then for shear strength and modulus. For the resilient modulus tests, the applied load was cyclic at 0.33-Hz frequency, and the maximum load used was set near the lower limit of the standards to ensure that the samples can be used in the shear testing.
 - The fourth group was tested for direct compression (CS) and the load was applied at a 50 mm/min rate
 - All tests were performed at room temperature
 - It is important to mention that the conditioning process for all samples included the following steps:
 - The samples were soaked in a warm water bath at 70° C for six hours,
 - The samples were cooled in a cooling water bath at 25 C for one hour, then

- The mechanical properties were evaluated, using all the abovementioned test methods.

4.5.4 Testing Results

4.5.4.1 Indirect tensile strength

The results of the indirect tensile strength test, which are presented in Table (4-15), showed that Mix4, Mix5, and Mix6 failed according to the PWGSC accept/reject criterion, except if the mix has 75% of retained strength. Mix1 and Mix7 both passed the required criterion. It is therefore possible to conclude that the ITS test was able to differentiate between the different mixes. However, the ITS test failed to differentiate between strippable and non-strippable mixes.

4.5.4.2 Resilient Modulus

Based on the PWGSC criteria, the presented results in Table (4-16) show that all the mixes pass, except Mix4. The test therefore seems reliable in predicting stripping for the tested mixes. However, one of the disadvantages of this test method is that it is quite time consuming compared to other test methods. In addition, special equipment and a data acquisition system is required to complete this test. Nevertheless, the resilient modulus is a very good indicator of long-term performance and shows strong reliability when identifying stripping for laid asphalt pavements. The resilient modulus test was able to differentiate between Mix4 and Mix5, and it passed Mix1, Mix6, and Mix7.

Table (4-15): Summary of the Results of the Indirect Tensile Strength Test Method

Sample #	Mix Type and Condition		Stresses (MPa)		Tensile Strength Ratio
	Condition	Mix Type	ITS	Average	TSR (%)
13	Dry	Mix1	1.33	1.27	79.5
14			1.24		
15			1.24		
4	Wet		1.06	1.01	
5			0.99		
6			0.97		
13	Dry	Mix4	2.28	2.03	65.0
14			2.42		
15			1.38		
4	Wet		1.1	1.32	
5			1.48		
6			1.38		
13	Dry	Mix5	1.39	1.40	65.7
14			1.39		
15			1.41		
4	Wet		0.92	0.92	
5			0.94		
6			0.89		
13	Dry	Mix6	0.99	1.07	73.8
14			1.1		
15			1.12		
4	Wet		Failed	0.79	
5			0.77		
6			0.81		
13	Dry	Mix7	1.11	1.05	84.8
14			0.98		
15			1.07		
4	Wet		0.95	0.89	
5			0.83		
6			0.88		

Table (4-16): Summary of the Results of the Resilient Modulus Test

Sample	Mix type and Condition		Side (MPa)		Average MPa	Average MPa	M _{RR} (%)
			Left	Right			
19	Dry	Mix5	1.45	1.45	1.45	1.08	86.13
20			0.85	0.84	0.85		
21			0.72	1.15	0.93		
22	Wet		0.89	0.96	0.92	0.93	
23			0.92	0.93	0.93		
24			Failed	Failed	Failed		
19	Dry	Mix4	0.56	0.81	0.69	0.86	70.69
20			1.14	0.90	1.02		
21			0.79	0.96	0.87		
22	Wet		0.79	0.48	0.63	0.61	
23			0.77	0.56	0.66		
24			0.49	0.56	0.53		
19	Dry	Mix1	0.30	0.47	0.38	0.45	86.35
20			0.27	0.57	0.42		
21			0.49	0.61	0.55		
22	Wet		0.45	0.38	0.41	0.39	
23			0.21	0.40	0.31		
24			0.41	0.49	0.45		
45	Dry	Mix6	0.58	0.53	0.55	0.62	96.08
46			0.49	0.56	0.52		
47			0.83	0.74	0.78		
1	Wet		0.78	0.74	0.76	0.60	
2			0.39	0.48	0.43		
3			Failed	Failed	Failed		
48	Dry	Mix7	1.23	1.05	1.14	0.97	84.28
49			1.22	0.77	1.00		
50			0.84	0.72	0.78		
1	Wet		0.46	0.60	0.53	0.82	
2			0.94	1.29	1.11		
3			Failed	Failed	Failed		

4.5.4.3 Marshall Stability

The Marshall Stability test method has the advantage of being able to identify the susceptibility of Canadian asphalt pavement mixes. The results in Table (4-17) illustrate that the Marshall Stability test method was able to identify stripping. The advantages of this test include its simplicity, its ability to predict stripping, and its accessibility in all asphalt laboratories. In addition, the results show that the method of “assuming PWGSC criterion of acceptance” passes the mixes that should pass and fails Mix4, which is known to be susceptible to stripping.

4.5.4.4 Shear Strength

SHRP recently adopted the shear strength test in order to predict rutting. Therefore, this test method was examined during phase 3 to evaluate its ability to predict stripping. The results presented in Table (4-18) show that the shear strength test method is not able to predict stripping. In addition, it was very complex and time consuming, since gluing the samples took 24 hours. Moreover, the plates that are glued to the samples require a special alignment during soaking in a warm water bath, which render the test very complicated.

Table (4-17): Summary of the Results of the Marshall Stability Test Method

Sample #	Mix Type and Condition		Stability (MPa)		Tensile Strength Ratio
	Condition	Mix Type	MS	Average	TSR (%)
16	Dry	Mix1	12.27	10.57	84.51
17			9.91		
18			9.53		
7	Wet		9.22	8.93	
8			8.09		
9			9.49		
16	Dry	Mix4	17.48	17.39	69.79
17			17.45		
18			17.23		
7	Wet		11.66	12.13	
8			12.83		
9			11.91		
16	Dry	Mix5	22.17	22.45	86.32
17			22.68		
18			22.51		
7	Wet		20.02	19.38	
8			18.68		
9			19.44		
16	Dry	Mix6	16.66	15.72	84.73
17			17.30		
18			13.19		
7	Wet		10.51	13.32	
8			15.47		
9			13.97		
16	Dry	Mix7	11.87	13.45	100.31
17			14.88		
18			13.59		
7	Wet		13.12	13.49	
8			13.71		
9			13.63		

Table (4-18): Summary of the Results of the Shear Strength Test Method

Sample Number	Mix Type and Condition		Shear Stress (MPa)		Shear Modulus (MPa)		Strength Ratio	
	Condition	Mix Type	SS	Average	SM	Average	SSR	SMR
19	Dry	Mix1		0.54	0.00	5.55	NA	NA
20			0.59		5.58			
21			0.49		5.51			
1'	Wet		0.00	Failed	0.00	Failed		
2'			0.00		0.00			
3'			0.00		0.00			
19	Dry	Mix4	0.97	1.05	10.53	12.23	69	55
20			0.87		12.19			
21			1.31		13.96			
1'	Wet		0.45	0.73	7.86	6.71		
2'			0.88		7.68			
3'			0.86		4.58			
19	Dry	Mix5	1.17	1.34	7.68	9.43	52	62
20			1.41		12.75			
21			1.45		7.86			
1'	Wet		0.49	0.70	3.72	5.85		
2'			0.73		6.21			
3'			0.89		7.61			
19	Dry	Mix6	0.57	0.68	3.60	3.99	86	85
20			0.76		4.72			
24			0.71		3.65			
40	Wet		0.73	0.59	4.68	3.39		
41			0.57		2.80			
42			0.47		2.69			
19	Dry	Mix7	1.04	0.94	11.17	8.09	27	18
20			0.94		6.31			
21			0.86		6.78			
44	Wet		0.26	0.26	1.45	1.45		
53								
54								

Table (4-19): Summary of the Results of the Direct Compression Test Method

Sample #	Mix Type and Condition		Stresses (MPa)		Tensile Strength Ratio
	Condition	Mix Type	ITS	Average	TSR
10	Dry	Mix1	0.89	0.91	44
11			0.93		
12			0.90		
1	Wet		0.32	0.40	
2			0.42		
3			0.45		
10	Dry	Mix4	1.14	1.11	56
11			1.10		
12			1.10		
1	Wet		0.52	0.63	
2			0.65		
3			0.71		
10	Dry	Mix5	1.38	1.37	79
11			1.34		
12			1.39		
1	Wet		1.07	1.08	
2			1.05		
3			1.12		
10	Dry	Mix6	1.30	1.33	65.7
11			1.36		
12			Failed		
1	Wet		0.93	0.87	
2			0.80		
3			0.89		
10	Dry	Mix7	1.39	1.34	89.8
11			1.44		
12			1.18		
1	Wet		1.00	1.08	
2			1.08		
3			1.15		

4.5.4.5 Direct Compression

The direct compression test method was expected to simulate the effect of the heavy static loads on the asphalt layer. The results presented in Table (4-19) show that the direct compression test method is not capable of predicting stripping, since it fails most of the mixes that are not compatible with the material properties of these mixes.

4.5.5 Remarks

Phase 2 investigates the test method that so far seems to be suitable at predicting stripping. The ITS, MS, CS, MR, and SS were used to evaluate the four different mixes out of which one of them was known to be susceptible to stripping. The summary of the results in Table (4-20) illustrates that only the Marshall Stability and the Resilient Modulus test methods were useful in evaluating the susceptibility of the Canadian asphalt pavement mixes. Moreover, the Marshall Stability test method has the advantage of being simple, fast, and accessible in all asphalt laboratories.

Table (4-20): Summary of Results of Phase 3

Test Method	Mix Type					Ranking
	Mix1	Mix4	Mix5	Mix6	Mix7	
Tensile Strength Ratio (TSR)	79.5	65.0	65.7	73.8	84.8	3
Resilient Modulus Ratio (M_R)	86.0	70.7	86.3	96.1	84.2	1
Marshall Stability Ratio (MSR)	84.5	69.8	86.3	84.7	100.3	2
Compression Strength Ratio (CSR)	44	56	79	65.7	89.8	4
Shear Strength Ratio (SSR)	0	69	52	86	27	5
Shear Modulus Ratio (SMR) "G"	0	46	62	85	18	6

5 ANALYSIS OF LABORATORY EXPERIMENTAL RESULTS

5.1 INTRODUCTION

The objective of this chapter is to present the statistical analysis for the results of the parametric investigation, including the construction factors (surface cracks and air voids content), the conditioning factors (warm and cool water bathes), the environmental factors (degree of saturation, and freeze thaw cycles), and the mechanical properties (phase3).

The analysis begins by testing the effects of the surface cracks on moisture-induced damage "TSR". Then, the analysis proceeds with an examination of the effects of the air voids content as independent variables with TSR as dependent variable at different soaking temperatures. Furthermore, the analysis of the conditioning duration (warm and cool water bathes) on the TSR will be carried out to evaluate the influence of the soaking duration on the rate of change in the TSR. In addition, the effects of environmental factors (freezing thaw, and degree of saturation) on the TSR will be examined.

Chapter 5 continues the investigation by presenting a statistical analysis for phase3 in order to facilitate the selection of an appropriate test method that is able to differentiate between susceptible and non-susceptible asphalt pavement mixes. The suitable test method has to be simple, correlated with other test methods, able to predict the long-term performance, and able to evaluate the stripping for different mixes.

5.2 ANALYSIS OF THE EFFECT OF SURFACE CRACKS ON TSR

The main objective of this analysis is to test the effect of construction cracks on the TSR, which represents stripping. The analysis of the effects of surface cracks was carried out in two stages: the first stage compared the ability of four standard test methods to evaluate the effect of surface cracks on the TSR, whereas the second stage investigated the relative relationship between the loading direction and the direction of the cracks on the ITS. The analysis of the first stage was carried out based on the observations presented in chapter 4, while the analysis of the second stage was carried out using the statistical analysis, which is presented in the next section.

In order to examine the effects of the field compaction induced surface cracks on the tensile strength, the t-test procedure was used. The null hypothesis was assumed to be $H_0: \mu_{ITS_{parallel}} = \mu_{ITS_{no-cracks}}$, also, $\mu_{ITS_{no-cracks}} = \mu_{ITS_{perpendicular}}$. Generally, if the test is performed at a level of confidence $\alpha = 0.05$, the p-value will be used to indicate whether to accept or reject the null hypothesis.

1. Accept the null hypothesis if the p-value is >0.05 .
2. Reject the null hypothesis if the p-value is ≤ 0.05 .

Based on the assumed $\alpha=0.05$, the results in Table (5-1) comparing the effect of the loading direction relative to the cracks direction. The samples were loaded parallel to the cracks direction, resulted in rejecting the null hypothesis in three out of the four cases. The results mean that the surface cracks has a significant effect on the ITS for Mix1 and Mix 2 for both dry and wet conditions. Moreover, comparing the effect of the

perpendicular loading with the none cracked field samples resulted in insignificant difference in three out of the four studied cases. It is important to mention that the detailed analysis are presented in appendix 5, and the variance between the compared data were equal in all cases.

The conclusion based on the analysis of the results showed that the construction cracks significantly affect the ITS which mean considering the surface cracks effect during the evaluation of the moisture induced damage is required to assure the correlation between laboratory evaluation and field performance.

Table (5-1): Summary of t-test for Indirect Tensile Strength of Cracked Field Samples

Mix	Condition	Loading Direction	Two-Tailed t-test	(df)	p-value
Mix1	Dry	Parallel	2.256	4	0.087
Mix1	Dry	Perpendicular	1.727	4	0.160
Mix2	Dry	Parallel	5.395	4	0.006
Mix2	Dry	Perpendicular	4.121	4	0.150
Mix1	Wet	Parallel	6.368	4	0.003
Mix1	Wet	Perpendicular	6.547	4	0.003
Mix2	Wet	Parallel	6.455	4	0.003
Mix2	Wet	Perpendicular	2.168	4	0.059

Level of significance (α) equal 0.05

The regression analysis was performed to determine the effect of construction factors on the TSR (surface cracks and air voids content) using the results shown in Tables (4-3) and (4-4). The regression analysis technique was used to examine the relationship between the construction effect and the TSR. The relationship between the surface cracks is combined with the air voids content as a parameter, whereas the second parameter is the TSR. During the first trial of modelling the relationship, the surface cracks were insignificant to the TSR, which was the main reason of combining these two factors. In order to quantify the cracks, it was assumed that cracks samples have 1.5, 2, 2.5, 3, 3.5, and 4 times the original air voids content. The suitable model, based on the obtained R^2 , was found when the cracked samples were assumed to have twice the original air voids content.

The non-linear analysis was found to best represent the relationship between the TSR and the construction factor. The quadratic, logarithmic, power, and exponential relationships were examined, using the Statistical Package for the Social Sciences “SPSS”, and the final developed relationship is shown in equation (5-1). The exponential relationship had the highest adjusted R^2 value of 0.917, and the estimator parameters were significant at $\alpha=0.05$, which means that the construction parameters are capable of explaining 91.7 percent of the variation within the TSR. The construction parameter includes the air voids content and cracks factor. The cracks factor equals 1 if the samples are free of cracks, and equals 2 if the samples are cracked.

Equation 5-1: Relationship between TSR and the Construction Parameter

$$\text{TSR} = 80.09 * \text{EXP (Construction parameter)}^{-0.0263}$$

5.3 REMARKS OF THE ANALYSIS OF SURFACE CRACKS

The first stage of the analysis of the results entailed a comparison of the different standard test methods through which the effects of surface cracks were evaluated, whereas the second stage aimed to evaluate the effect of the direction of the cracks on the ITS. Based on the observations mentioned in section 4.3 and the statistical analysis presented in section 5.2, the following remarks can be made:

1. Surface cracks were found to affect the ITS significantly, whereas the conditioning process did not significantly affect the ITS of the cracked samples.
 - a. Comparing laboratory samples and cracked field cores, the reduction in the TSR due to surface cracks for Mix1 ranged from 4.3% to 16.6%, while the range for Mix2 was 3.5% to 62.7%.
 - b. During the comparison between the cracked and none cracked field cores, the average reduction was found to range from -9.5% to 30.1% for Mix1, while the reduction for Mix2 was ranged from -12.0 %to 47.7%.
2. Investigating the loading direction relative to the direction of the cracks on the ITS and the TSR, perpendicular loading techniques were found to yield a higher TSR than parallel loading techniques for all cases:
 - a. Comparing cracked and non-cracked field samples, the perpendicular loading yields a higher ITS for Mix1 at 4.4% for dry samples at 25°C and 8.5% for conditioned samples at 70°C. The difference between 4.4% and

8.5% is due to the conditioning of the samples. Moreover, the same change for Mix 2 was 9.0 % and 38.0 % respectively.

- b. The effects of the surface cracks on the ITS were higher for Mix2 than Mix1, which could be due to the difference between the air voids content.
 - c. Comparing TSR of the laboratory samples and cracked field cores proved that the average reduction in the TSR due to cracks was 14% for Mix 1 and 24% for Mix 2. In addition, comparing cracked and non-cracked field cores confirmed that cracks reduce the TSR by 6 % and 14 % for mixes 1 and 2 respectively.
3. The presented relationship relates the air voids content and surface cracks to the TSR showed that both parameters significantly affect the TSR.
 4. Since the evaluation of stripping is based on laboratory prepared samples; the findings of this section proved that surface cracks is one of the reasons for the lack of correlation between laboratory test methods and field long term performance. Therefore, it is recommended to reduce the laboratory measured TSR by 10 to 20% due to the effect of surface cracks.

5.4 ANALYSIS OF THE RESULTS OF THE EFFECT OF AIR VOIDS CONTENT ON TSR

In order to investigate the effects of air voids content on the TSR, the regression analysis was carried out in two stages. The first stage entailed four mixes with one

soaking temperature, while the second stage included two mixes with three different soaking temperatures. The analysis of the first stage began by identifying the relationship between stripping and air voids content using the regression analysis. The curve estimator technique was carried out to investigate the nature of the relationship between air voids content and the TSR at different soaking temperatures. The details of the analysis are shown in Appendix 5 and for each soaking temperature, the linear, quadratic, power, and exponential relationships were examined. It was found that the linear and exponential relationship might be used to fit the results at 60° C soaking temperature, while the quadratic relationship seems more suitable for 70 ° C. Moreover, at 80° C soaking temperature, the samples failed before they were even tested.

The linear relationships, which are plotted in Figure (5-1), showed that Mix 4 starts with a high value of the TSR. However, the rate of strength loss with an increase of air voids content was very high, compared to other mixes. The observations found that above a certain level of air voids content, the probability of identifying stripping is more likely to occur. Figure (5-1) illustrates that the linear trend of Mix 4 is intersecting with Mix 3 at 7.4 % of air voids content and with Mix 5 at 8.6%. Furthermore, Mix 1 and Mix 4 seem to intersect at a higher percentage of air voids content. The air voids content for mix 1 was less than any other mix for the same level of compaction.

In general, it is possible to conclude that the more using of critical the air voids content, during preparing the laboratory samples the more likely it is to identify stripping. Based on the shown results and field observations the critical air voids content should be considered more than 8.6%.

Figure (5-1): Relationships between Air Voids Content and TSR at 60° C

The second stage of analyzing the effects of air voids content included using soaking temperatures at 70° C and 80° C on conditioned samples by means of Mix4 and Mix5. The results showed that the difference of the TSR between strippable and non-strippable material could be identified at any level of air voids content. However, the difference was more observable when the used air voids content was more than 8.6 %. Furthermore, the critical air voids content should be decided based on the required TSR. The type of equations at different soaking temperatures, which are shown in Figure (5-2), are listed in Table (5-2).

Table (5-2): Summary of Regression Analysis of the Soaking Temperature Effect

Mix Type	Type of Trend	R ²	Significance	Note	Temperature
Mix-4	Linear	0.9640	0.0019	Susceptible to Moisture Damage	60°C
Mix-4	Quadratic	0.9660	0.0170		70°C
Mix-4	Logarithmic	0.6490	0.0627		80°C
Mix-5	Linear	0.8190	0.0221	Not Susceptible to Moisture Damage	60°C
Mix-5	Quadratic	0.9770	0.0117		70°C
Mix-5	Logarithmic	0.794	0.1032		80°C

Figure (5-2): Relationships between Air Voids Content and TSR at Different Temperatures.

The correlation between the air voids content and the TSR for the four examined mixes at 60 °C, were examined and presented in Table (5-3). The correlation matrix illustrates that there is a highly negative correlation between air voids content and the TSR. The air voids content and the TSR were highly correlated at $\alpha=0.01$ for Mix1 and Mix4 while for Mix5 α was at 0.05. However, Mix3 was the only Mix that had α more than 0.05, which means that the correlation was not significant at $\alpha=0.05$.

Table (5-3): The correlation matrix between air voids content and TSR

Tensile Strength Ratio		Air Voids Content and TSR			
		Mix1	Mix3	Mix4	Mix5
	Mix1	-0.985** $\rho = 0.002$ N=5	-0.829 $\rho = 0.083$ N=5	-0.986** $\rho = 0.002$ N=5	-0.930* $\rho = 0.022$ N=5

*Significant at 0.05 significant level

** Significant at 0.01 significant level

Figure (5-1) summarizes the results and shows that stripping can be identified when the air voids content is more than 8.6% in most cases, whereas the relationship between air voids and the TSR could be either linear or exponential. The analysis of the second stage was carried out by using two mixes with three different soaking temperatures. The results are plotted in Figure (5-2) for soaking temperatures at 60 °C, 70 °C, and 80 °C respectively. In addition, Table (5-2) shows the developed models for these temperatures and the ρ values for each model. It is significant to mention that the

relationships were valid at a level of confidence $\alpha=0.05$ for 60° C and 70° C. In addition, the correlation between the air voids content and the TSR was examined and presented in Table (5-3).

Based on the observations and the analysis, the following recommendation can be made:

- A soaking temperature of 70° C should be used, since the stripping was easily identified when the samples were prepared in the laboratory with an air voids content >8.6%.

5.5 REMARKS ON THE ANALYSIS OF THE AIR VOIDS CONTENT RESULTS

The conclusion for this investigation could be summarized into two main findings:

- Samples should be prepared with an Air voids content ≥ 8.6 % for stripping evaluation.
- It is recommended to soak the conditioned samples at 70° C.
- The air voids content is highly correlated to the TSR (stripping).

5.6 ANALYSIS OF THE EFFECT OF WARM WATER BATH SOAKING DURATION ON TSR

The analysis of the results starts with a descriptive statistic and is followed by a regression analysis in order to model the relationship between the ITS and the soaking duration. The descriptive statistics shown in Table (5-4) include the maximum and

minimum values, mean and standard deviations of the ITS. As it is known that the standard deviation measures the variability of the data-set. Based on concept of Bell curve, 68 % of the data points always fall within one standard deviation of the mean and 95% fall within two standard deviations of the mean. Furthermore, if the data falls outside the 95% percent zone, then it is very likely that there is a data problem. Looking to the available data showed that the available data most likely passes this criterion (Kaplan 1987).

Table (5-4): Descriptive Statistics of the Results of the Soaking Duration Effect.

	N	Minimum	Maximum	Mean	Std. Deviation
Mix1-Lab	8	.19	.45	.2838	.08911
Mix4-Lab	8	.13	.38	.2113	.08079
Mix5-lab	8	.10	.35	.1763	.08684
Mix2-Field	8	.02	.15	.0613	.04291
Mix1-Field	8	.04	.17	.0738	.04470
Valid N (listwise)	8				

The curve estimator technique was used to examine the relationship between the ITS and the soaking duration. Figure (5-3) shows the trend for five different mixes. Based on the findings, the power trend could be used, since it properly fits the data, and the dependent variable will always have a positive value. The power trend starts with a very high rate of change of the dependent variable (ITS_w) with the change of the independent variable (soaking duration), then it slows down the rate of change.

Figure (5-3): The Trend of the Relationship between Soaking Duration and ITS

The next step in this approach is to calculate the slope for the developed relationship for each mix, which is shown in Table (5-5). The developed relationship between the soaking duration and the ITS for all mixes has p -values less than 0.01, which means that they are significant at level of confidence $\alpha=0.01$.

Table (5-5): Warm Water Bath Duration Modules and Derivatives

Mix Type	Module	R ²	p-values	Slope
Mix-1-Lab	$Y=0.322X^{(-0.187)}$	0.942	0.0001	$Y'=(-0.060) X^{(-1.187)}$
Mix-1-Field	$Y=0.086X^{(-0.328)}$	0.904	0.0003	$Y'=(-0.028) X^{(-1.328)}$
Mix-2-Field	$Y=0.072X^{(-0.424)}$	0.858	0.0010	$Y'=(-0.031) X^{(-1.424)}$
Mix-4-Lab	$Y=X^{(-0.222)}$	0.935	0.0001	$Y'=(-0.222) X^{(-1.222)}$
Mix-5-Lab	$Y=0.206X^{(-0.283)}$	0.941	0.0001	$Y'=(-0.206) X^{(-1.283)}$

To calculate the rate of change of the TSR_w for different soaking durations, it is required to substitute different soaking durations into the equations shown in Table (5-5). Table (5-6) shows the calculated values while Figure (5-5) shows the plotting of these values. The plot of the rate of change shows that it starts at a very high level and decreases dramatically. Three hours of soaking causes a loss of strength of more than 95%, while six hours of soaking causes a loss of more than 98%. Moreover, the strength rate difference between eight and twenty four hours of soaking is less than 2%. Based on the above analysis, it is recommended that Table (5-7) be used to choose the soaking duration based on the required accuracy level. During the next stages of this research, it is recommended to use six hour soaking duration in the warm water bath.

Table (5-6): Rate of Change of the Indirect Tensile Strength with the Soaking Duration

Duration (Hour)	Mix Type						
	Lab Mix1	Field Mix1	Field Mix2	Lab Mix4	Lab Mix5	Average	Average retained Rate of change of TSR _w
	Rate of Change of ITS (KPa/min)						
0.25	-312.06	-177.74	-219.60	-1208.01	-345.82	-452.65	100.00
0.5	-137.06	-70.80	-81.84	-517.86	-142.11	-189.93	41.96
1	-60.20	-28.20	-30.50	-222.00	-58.40	-79.86	17.64
2	-26.44	-11.23	-11.37	-95.17	-24.00	-33.64	7.43
3	-16.34	-6.56	-6.38	-57.98	-14.26	-20.30	4.49
4	-11.61	-4.47	-4.24	-40.80	-9.86	-14.20	3.14
5	-8.91	-3.33	-3.08	-31.06	-7.41	-10.76	2.38
6	-7.18	-2.61	-2.38	-24.86	-5.86	-8.58	1.90
7	-5.98	-2.13	-1.91	-20.59	-4.81	-7.08	1.57
8	-5.10	-1.78	-1.58	-17.49	-4.05	-6.00	1.33
9	-4.44	-1.52	-1.33	-15.14	-3.48	-5.18	1.15
10	-3.91	-1.33	-1.15	-13.32	-3.04	-4.55	1.01
16	-2.24	-0.71	-0.59	-7.50	-1.67	-2.54	0.56
24	-1.38	-0.41	-0.33	-4.57	-0.99	-1.54	0.34

Figure (5-4): Plot of the Rate of Change versus Soaking Duration

5.7 REMARKS ON THE ANALYSIS OF WARM WATER BATH DURATION

Based on the previous analysis, it is possible to conclude that the warm water bath duration affects the retained strength of the tested samples. Clearly, the trend of the rate of change of the retained strength decreases with an increase in the soaking duration. Table (5-6) shows the rate of change of the percentage rate of the retained strength versus the soaking duration, whereas Figure (5-4) shows the plot of these results, which illustrates that after three hours, the average retained percentage of rate of change of TSR_w for all mixes is less than 5%, while after six hours the retained percentage dropped to 2%. This observation confirmed that six hour soaking in the warm water bath is

enough to condition the samples. If the recommended duration (6 hours) is used, the total test duration may be reduced to 8 hours. In addition, the developed equations of the rate of change could be used to calculate any required rate of change by changing the soaking time.

5.8 ANALYSIS OF THE RESULTS OF THE EFFECT OF COOLING DURATION ON TSR

The same technique used to analyze the soaking duration for the warm water bath was carried out to analyze the effects for the cooling water bath duration. The descriptive statistics are shown in Table (5-7) and include maximum and minimum values, mean, and standard deviations. As it was mentioned before, the standard deviation describes the variability of the data (Kaplan 1987), the available data seem to fall within two standard deviation of the mean.

Table (5-7): Descriptive Statistics for cooling duration effect on the ITS

Mix Type	N	Minimum	Maximum	Mean	Std. Deviation
MIX1-LAB	5	.99	1.21	1.0900	.08746
MIX1-FIELD	5	.07	.14	.1020	.02775
MIX2-FIELD	5	.29	.39	.3360	.04099
MIX6-LAB	5	.53	.91	.7320	.17413
MIX7-LAB	5	.82	1.20	1.0680	.15156
Valid N (listwise)	5				

The TSR for each duration was calculated and listed in Table (5-8) showed that the average increase in the TSR is 36% after one hour, 44 % after two hours, and drops to 41 % after three hours of cooling.

Table (5-8): Summary of the (TSR), Results of the Cooling Duration

Duration (Minutes)	Lab Mix1	Field Mix1	Field Mix2	Lab Mix 6	Lab Mix7	Average
	Percentage of Increase of (TSR)					
15	100	100	100	100	100	100
30	104	114	117	106	127	113
60	109	157	117	157	143	136
120	115	157	130	172*	146	144
180	122	194*	97*	157	135*	141

Furthermore, Table (5-9) showed that when the outliers were excluded, the average increase in the TSR is 36 % after one hour of cooling, 37 % after two hours, and 39 % after three hours of cooling. The obtained results means that the samples gain most of their strength after one hour of cooling, while the next two hours only increase the TSR by 2%. Moreover, Figure (5-5) shows that the average increases of the TSR with a cooling duration are almost constant between one and two hours of cooling. Also, observing the plotted relationships between the cooling duration and the ITS, shown in Figure (5-6), exemplifies that the change of the TSR after one hour of cooling is almost constant.

Figure (5-5): The Trend of the Change of the (TSR)_c for Different Cooling Durations

Table (5-9): The Modified Summary of the (TSR)_c Results of the Cooling Duration

Duration (Minutes)	Lab Mix1	Field Mix1	Field Mix2	Lab Mix 6	Lab Mix7	Average
	Percentage of Increase of (TSR)					
15	100	100	100	100	100	100
30	104	114	117	106	127	113
60	109	157	117	157	143	136
120	115	157	130		146	137
180	122			157		139

Table (5-10): Summary of the Regression Analysis of the Cooling Duration Effect on the ITS.

Mix Type	Module	R ²	p-values	Slope
Lab Mix1	$Y=0.746+0.085 \ln X$	0.965	0.0029	(0.085/X)
Field Mix1	$Y=0.0263 \ln X$	0.911	0.0116	(0.0263/X)
Field Mix2	$Y=0.039 \ln X$	0.895	0.0542	(0.039/X)
Lab Mix6	$Y=-0.055+0.203 \ln X$	0.910	0.0462	(0.203/X)
Lab Mi-7	$Y=0.371+0.183 \ln X$	0.900	0.0517	(0.183/X)

Figure (5-6): The Relationship between Cooling Duration and ITS

The summary of the output of the regression analysis is shown in Table (5-10), which includes the R^2 , p –values, and the derivative of each model. In addition, the statistical analysis investigates the effects of different cooling durations on the ITS.

In addition, the presented slopes of these equations represent the rate of change of the ITS as dependent variable “Y”, while the cooling duration is represented by the independent variable “X”. These derivatives (Y’) are used to initiate Table (5-11), which presents different values of the rate of change at different cooling durations for five mixes. Figure (5-7) plots the relationship between the rate of change of the ITS versus the soaking duration in the cooling water bath. Based on the analysis and the plotted rate of change of the ITS versus the cooling duration, it is recommended that one hour of cooling be used as a guideline for the newly developed test method.

Table (5-11): The Absolute Rate of Change of the ITS versus the Cooling Duration

Duration (Min)	Mix Type					
	Lab Mix1	Field Mix1	Field Mix2	Lab Mix 6	Lab Mix7	Average
	Rate of Change of ITS (KPa/min)					
15	2.83	0.88	1.30	6.77	6.10	7.15
30	1.89	0.58	0.87	4.51	4.07	3.58
45	1.42	0.44	0.65	3.38	3.05	2.38
60	1.13	0.35	0.52	2.71	2.44	1.79
75	0.94	0.29	0.43	2.26	2.03	1.43
90	0.81	0.25	0.37	1.93	1.74	1.19
105	0.71	0.22	0.33	1.69	1.53	1.02
120	0.47	0.15	0.22	1.13	1.02	0.89
180	2.83	0.88	1.30	6.77	6.10	0.60

5.9 REMARKS OF THE ANALYSIS OF COOLING DURATION

Considering the analysis and results above, it is possible to conclude that the cooling duration affects the ITS of the tested samples for different mixes. The results in Table (5-9) show that the average change of the TSR for all mixes between one and two hours of cooling is 1 %. Therefore, it is recommended that one hour of cooling is to be used for the new guidelines.

Figure (5-7): Plot of the Rate of Change of the ITS versus the Cooling Duration

5.10 ANALYSIS OF THE EFFECT OF THE ENVIRONMENTAL FACTORS ON TSR

The analysis of the effect of the freezing duration on the ITS additionally carried out a t-test to study the effect of freeze on different mixes. The analysis compared freezing durations of 0, 2, 4, 16, 24, and 48 hours using a t-test. The results of the significance of the freezing duration on the ITS for each mix are presented in Table (5-12). The null hypothesis assumes that the two means of the variable are equal H_0 : $\mu_{ITS\text{Freezing}} = \mu_{ITS\text{no-freezing}}$. Accepting the null hypothesis means that the freezing duration of the tested samples does not affect the ITS, while rejecting the null hypothesis means the opposite. The results in Table (5-12) show that Mix1-Field, and Mix 7-Laboratory have accepted the null hypothesis while Mix2-Field, and Mix 6 Laboratory have rejected the null hypothesis. Therefore, the test was inconclusive as to whether or not freezing thaw may be included in the conditioning process of the developed guidelines. Figure (5-8) presents the plot of the freezing duration versus the TSR for different mixes. The plot shows that the two hours of freezing with a degree of saturation (not less than 70%) has the lowest value of TSR.

Table (5-12): Summary of the t-test for Different Freezing Durations

Mix	Duration of Freezing	t-Statistic	(df)	p-Value
Mix1	2	10.845	4	0.000
Mix1	4	14.148	4	0.000
Mix1	16	6.037	4	0.004
Mix1	24	9.297	4	0.001
Mix1	48	7.439	4	0.002
Mix2	2	0.387	4	0.712
Mix2	4	-0.294	4	0.783
Mix2	16	-0.052	4	0.961
Mix2	24	NA	NA	NA
Mix2	48	NA	NA	NA
Mix6	2	2.861	4	0.046
Mix6	4	0.644	4	0.555
Mix6	16	0.814	4	0.461
Mix6	24	0.986	4	0.380
Mix6	48	2.440	4	0.071
Mix7	2	2.606	4	0.06
Mix7	4	3.632	4	0.022
Mix7	16	3.580	4	0.023
Mix7	24	3.027	4	0.039
Mix7	48	8.8505	4	0.001

Significant level (α) = 0.05

Figure (5-8): The Effect of Freezing-thaw and Degree of Saturation on TSR

The Analysis of variance, ANOVA, was carried out to test the null hypothesis that the population of several means are equal. As is shown in Table (5-13), Mix 1 and Mix 2 have p-values 0.000 and 0.002 respectively, which means that they reject the null hypothesis. On the other hand, mix6 and mix7 have p-values equal to 0.08 and 0.052, which means that they accept the null hypothesis. The ANOVA results confirmed the t-test and exemplified that there is no complete agreement on the affects of freezing duration on the ITS.

In summary, the freezing duration, as well as the degree of saturation, could be excluded or included into the new guideline for the stripping tests. In case of an inclusion of the degree of saturation, a 70% degree of saturation and a 2.0 hours of freezing duration is recommended.

Table (5-13): Summary of the ANOVA results

Mix #		Sum of Squares	df	Mean Square	F	P-values
MIX6	Between Groups	.243	5	.049	2.612	.080
	Within Groups	.224	12	.019		
	Total	.467	17			
MIX7	Between Groups	1.474	5	.295	3.073	.052
	Within Groups	1.152	12	.096		
	Total	2.626	17			
MIX1Lab	Between Groups	.232	5	.046	45.639	.000
	Within Groups	.012	12	.001		
	Total	.244	17			
MIX2Field	Between Groups	.032	3	.011	13.528	.002
	Within Groups	.006	8	.001		
	Total	.039	11			

5.11 REMARKS ON THE ANALYSIS OF THE ENVIRONMENTAL FACTOR

Based on the discussion above, there is no agreement on the environmental factor's affect on the TSR. However, since we are dealing with a Canadian climate including freezing winters and hot summers, it is recommend (optionally) to apply a 2 hour freezing period at -16°C , followed by a six hour warm water bath. In addition, it is recommended to use a degree of saturation at 70%. This recommendation is based on the ANOVA and t-test, as well as the observations. Finally, it is recommended to extend the work herein and refine the freezing duration measurements (0.15, 0.30, 0.45, 1.0 ...) in order to examine the suitable freezing durations for stripping tests.

5.12 SUMMARY OF THE REMARKS OF PHASE 2.

Based on the observations and the analysis of the results of the parametric investigation, the following recommendations can be summarized:

1. Based on the investigation of the effects of air voids content on the TSR, it is recommended to prepare the laboratory sample with an air voids content more than or equal to 9%.
2. For the conditioning of the samples in the warm water bath, the soaking temperature is recommended to be at 70°C .
3. It is recommended to soak the sample for six hours in the warm water bath and to follow the bath with a one hour cooling period.

4. It is recommended to reduce the laboratory TSR to a minimum of 10% due to the effect of surface cracks.
5. The analysis showed that the construction parameter and the TSR are exponentially related.
6. There was no agreement on the effect of environmental factors on the TSR. However, it is optional to use 2 hours of freezing and a minimum degree of 70% saturation.

5.13 ANALYSIS OF THE RESULTS OF PHASE 3

Since a statistical analysis offers more insight into the significance of the results, the objective of this statistical analysis is twofold: First, it will examine whether these test methods could be used to differentiate between strippable and non-strippable mixes, and second, it will evaluate whether there is a correlation between various test methods. Consequently, the ideal test method should accomplish the following criteria:

- Be capable of passing and failing different mixes based on their performances (assuming its 50% of the required criteria),
- Be able to distinguish between a variety of long-term performances of different mixes (assuming its 20% of the required criteria),
- Have a good correlation with other test methods (assume it is 20% of the required criteria)
- Be relatively simple and fast test methods (10%).

Based on these criteria, the analysis of variance was carried out and the correlation between these test methods was examined. The analysis of variance, or ANOVA, is a method of testing the null hypothesis that several group means are equal in the population, by comparing the sample variance estimated from the group means to that estimated within the groups. The null hypothesis assumed that $H_0: \mu_{\text{Mix1}} = \mu_{\text{Mix4}} = \mu_{\text{Mix5}} = \mu_{\text{Mix6}} = \mu_{\text{Mix7}}$; where the μ 's are the mean values of each test parameter corresponding to the different mix types. Tables (5-14) and (5-15) show a summary of the results of an analysis of variance (ANOVA) performed to test the significance of the difference between the mean values of each test parameter corresponding to each mix type for the dry samples, and wet samples respectively.

As shown in Table (5-14), all test methods yield a significant difference between the five mixes tested at a level of significance, $\alpha = 5\%$. Therefore, the result of ANOVA shows that all test methods could be used to differentiate different long-term performances. Table (5-15) shows the results of ANOVA for the wet samples and illustrates that ITS, MS, and CS test methods yield a significant difference between the five mixes tested at a level of significance, $\alpha = 5\%$, while M_R , SS, and SM could not differentiate between the tested mixes. In short, it is possible to conclude that the Indirect Tensile Strength test, Marshall Stability, and Direct compression test are the only test methods that could be used to differentiate between different performances of the examined mixes.

Table (5-14): Summary of the ANOVA for the Dry Samples

Test		Sum of Squares	df	Mean Square	F	Sig.
ITS	Between Groups	1.896	4	.474	7.166	.005
	Within Groups	.661	10	.066		
	Total	2.557	14			
M _R	Between Groups	.799	4	.200	5.132	.016
	Within Groups	.389	10	.039		
	Total	1.188	14			
MS	Between Groups	238.850	4	59.712	31.559	.000
	Within Groups	18.921	10	1.892		
	Total	257.771	14			
CS	Between Groups	.457	4	.114	23.807	.000
	Within Groups	.043	9	.005		
	Total	.500	13			
SS	Between Groups	1.047	4	.262	12.213	.001
	Within Groups	.193	9	.021		
	Total	1.240	13			
SM	Between Groups	120.040	4	30.010	7.182	.007
	Within Groups	37.608	9	4.179		
	Total	157.648	13			

Table (5-15): Summary of the ANOVA for the Wet Samples

		Sum of Squares	df	Mean Square	F	Sig.
ITS	Between Groups	.455	4	.114	11.197	.002
	Within Groups	.091	9	.010		
	Total	.546	13			
MR	Between Groups	.422	4	.106	3.048	.094
	Within Groups	.242	7	.035		
	Total	.664	11			
MS	Between Groups	171.954	4	42.988	27.017	.000
	Within Groups	15.912	10	1.591		
	Total	187.865	14			
CS	Between Groups	1.057	4	.264	51.971	.000
	Within Groups	.051	10	.005		
	Total	1.108	14			
SS	Between Groups	.188	3	.063	1.610	.283
	Within Groups	.233	6	.039		
	Total	.421	9			
SM	Between Groups	31.216	3	10.405	3.658	.083
	Within Groups	17.067	6	2.844		
	Total	48.282	9			

The second stage of the analysis carried out a t-test to examine the effect of the conditioning on the ITS. The null hypothesis tested the equality of the mean values of the conditioned and unconditioned samples for different mixes. The null hypothesis was accepted if the p-value > 0.05 and rejected if the p-value is ≤ 0.05 . The equality of the variance of each two set of data were checked and presented in appendix 4, which showed that the variances are equal in all cases except the ITS for the conditioned and unconditioned samples.

The results of the t-test, which are presented in Table (5-16), show that the ITS test Marshall Stability, and direct compression test methods were able to identify the difference between the conditioned and unconditioned samples in most of the cases by rejecting the null hypothesis. Conversely, M_R , SS, and SM were accepting the null hypothesis in most of the cases, which means that they were not able to differentiate between the conditioned and unconditioned samples. Therefore, the ITS, MS, and direct compression could be used to test stripping.

Table (5-16): Summary of t-test results

Mix	Test	t-Statistic	(df)	p-Value
Mix1	ITS	6.494	4	0.003
Mix1	M _R	0.625	3	0.577
Mix1	MS	8.708	4	0.016
Mix1	CS	12.410	4	0.000
Mix1	SS	NA	NA	NA
Mix1	SM	NA	NA	NA
Mix4	ITS	2.048	4	0.110
Mix4	M _R	2.455	4	0.070
Mix4	MS	14.418	4	0.000
Mix4	CS	8.443	4	0.001
Mix4	SS	1.655	4	0.173
Mix4	SM	3.796	4	0.019
Mix5	ITS	30.026	4	0.000
Mix5	M _R	0.908	4	0.415
Mix5	MS	7.389	4	0.002
Mix5	CS	11.232	4	0.000
Mix5	SS	4.400	4	0.012
Mix5	SM	1.780	4	0.150
Mix6	ITS	5.160	3	0.014
Mix6	M _R	0.133	3	0.902
Mix6	MS	5.454	4	0.028
Mix6	CS	8.390	3	0.004
Mix6	SS	0.950	4	0.396
Mix6	SM	0.809	4	0.464
Mix7	ITS	3.214	4	0.032
Mix7	M _R	0.601	3	0.590
Mix7	MS	-0.045	4	0.966
Mix7	CS	2.867	4	0.046
Mix7	SS	6.594	2	0.022
Mix7	SM	2.144	2	0.165

Finally, the degree of agreement or disagreement between the different test methods as tools for long-term performance can simply be investigated based on the correlation between the results of the test methods. Tables (5-17) and (5-18) show the values of the Pearson correlation coefficient (r) and the level of significance, p -value, required for significant correlation. Table (5-17) presents the correlation coefficient for the unconditioned samples, while Table (5-18) presents the conditioned samples.

The results in Table (5-16) show that a high correlation exists between MS and both, M_R , and SS is significant at $\alpha = 1\%$, and with the CS at $\alpha = 5\%$. The ITS was only correlated to the SM at $\alpha = 5\%$. Furthermore, the SS was correlated with SM at $\alpha = 1\%$. The correlation matrix of the wet samples showed that MS was correlated with M_R and CS at $\alpha = 1\%$.

Generally, and based on the experimental investigation, the Marshall Stability Test, the Indirect Tensile Strength Test, and the Direct Compression Test methods could be rated as simple and fast since they take less time to test one sample, compared to the Resilient Modulus and the Shear Strength test. In addition, the equipment availability in most asphalt laboratories is easily applied to the above mentioned tests. Moreover, the Resilient Modulus Test Method takes one to two hours in order to evaluate one sample, not withstanding the more complicated calculations. Furthermore, it takes one day in order to glue the samples for the Shear Strength Test and the samples might fail during conditioning process.

Table (5-17): Correlations Between Different Test Methods for Dry Samples

		ITS	M _R	MS	CS	SS	SM
ITS	Pearson Correlation	1	.041	.292	-.250	.191	.564*
	Sig. (2-tailed)		.885	.290	.390	.512	.036
	N	15	15	15	14	14	14
M _R	Pearson Correlation	.041	1	-.694**	-.531	-.305	.174
	Sig. (2-tailed)	.885		.004	.051	.290	.552
	N	15	15	15	14	14	14
MS	Pearson Correlation	.292	-.694**	1	.620*	.764**	.376
	Sig. (2-tailed)	.290	.004		.018	.001	.186
	N	15	15	15	14	14	14
CS	Pearson Correlation	-.250	-.531	.620*	1	.513	-.007
	Sig. (2-tailed)	.390	.051	.018		.073	.981
	N	14	14	14	14	13	13
SS	Pearson Correlation	.191	-.305	.764**	.513	1	.692**
	Sig. (2-tailed)	.512	.290	.001	.073		.006
	N	14	14	14	13	14	14
SM	Pearson Correlation	.564*	.174	.376	-.007	.692**	1
	Sig. (2-tailed)	.036	.552	.186	.981	.006	
	N	14	14	14	13	14	14

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

Table (5-18): Correlations between different Test Methods for Wet samples

		ITS	M _R	MS	CS	SS	SM
ITS	Pearson Correlation	1	.031	-.329	-.436	.513	.470
	Sig. (2-tailed)		.928	.251	.119	.158	.202
	N	14	11	14	14	9	9
M _R	Pearson Correlation	.031	1	-.709**	-.418	.075	.181
	Sig. (2-tailed)	.928		.010	.177	.847	.642
	N	11	12	12	12	9	9
MS	Pearson Correlation	-.329	-.709**	1	.757**	.083	.067
	Sig. (2-tailed)	.251	.010		.001	.820	.855
	N	14	12	15	15	10	10
CS	Pearson Correlation	-.436	-.418	.757**	1	-.039	-.308
	Sig. (2-tailed)	.119	.177	.001		.915	.386
	N	14	12	15	15	10	10
SS	Pearson Correlation	.513	.075	.083	-.039	1	.626
	Sig. (2-tailed)	.158	.847	.820	.915		.053
	N	9	9	10	10	10	10
SM	Pearson Correlation	.470	.181	.067	-.308	.626	1
	Sig. (2-tailed)	.202	.642	.855	.386	.053	
	N	9	9	10	10	10	10

** Correlation is significant at the 0.01 level (2-tailed).

In order to summarize the analysis, Table (5-19) indicates various criteria, against which the tests are evaluated, including simplicity, speed, and the ability to differentiate between stripped and non-stripped asphalt mixes. The selection of the suitable test method is based on an achievement of the evaluation criteria. The test that corresponds to most of the criteria will be recommended to be used as an indicator of the mechanical properties of the tested samples during the stripping evaluation. Based on Table (5-19), it can be concluded that the Marshall Stability test method is most suitable for evaluating the susceptibility of stripping for the tested mixes. The Resilient Modulus Test method can only be a second choice, since it is more time consuming and lacks correlation with various other test methods. The rest of the test methods however, could not meet the required criteria. The Shear Strength and the Shear Modulus as parameters could not identify stripping, which is the most important and complex condition in terms of the tested procedures. In addition, the Direct Compression test and the Indirect Tensile Strength test methods failed to identify stripped and non-stripped mixes. It is important to mention that changing the percentage of each criterion will not change the selected test method under the condition of assuming failing and passing the mixes for stripping as the most important criteria.

Table (5-19): The Evaluation Criteria for stripping assessment

Test Method	Evaluation Criteria				% 100
	Failing and Passing Different Mixes for Stripping	Predicting the Long term performance	Correlation with other test Methods	Simplicity	
ITS	zero	20	zero	10	30
MR	50	zero	zero	5	55
MS	50	20	20	10	100
SS	zero	20	zero	zero	20
CS	zero	20	zero	10	30

5.14 REMARKS ON PHASE 3

This phase presented an experimental investigation aimed at assessing the relationship between different laboratory testing methods, evaluating the susceptibility and predicting the long-term performance of asphalt concrete pavements. The stripping of five standard mixes was tested in five different laboratory testing procedures resulting in six parameters per mix type. The parameters were compared to identify their potential to recognize the variability in performance with mix type. The results showed that the Marshall stability test method and the resilient modulus were able to rank the expected performance of asphalt mixes and their susceptibility to stripping. Moreover, a high correlation exists between the two parameters. In addition, the difference between the results for the five mixes was statistically significant, implying high confidence in their potential as indicators of long-term performance. The evaluation according to shear strength, shear modulus, ITS and CS were very weak and it is not possible to use these

tests to evaluate the susceptibility of asphalt mixes to stripping. However, the difference in mean values of SS, SM, CS, ITS, MS, and M_R for the different mixes was statistically significant, reflecting good potential as indicators of long-term performance.

It is important to note that the degree of simplicity/complexity of the examined test methods varies widely, as do their cost and testing time. More importantly, single parameters that may be good indicators of one pavement performance might serve poorly considering another performance, as was evident for shear strength, direct compression, and indirect tensile strength. It is therefore recommended to expand this work to include more mixes, more variables within each mix (for example, aggregate type and gradation and asphalt cement content), more testing conditions (for example, testing temperature, loading rate, stress level in resilient modulus), and more tests (for example, in-situ shear strength, complex modulus, and fatigue). Finally, based on the analysis and observations of the available results and the evaluation of the examined test methods, which is shown in Table (5-19); it is recommended to use the Marshall Stability test to evaluate stripping for Canadian airfield and highway mixes due to its higher performance and correlation with other test methods. Moreover, the resilient modulus test method could be the second alternative despite its disadvantages.

6 PERMEABILITY INVESTIGATION

6.1 INTRODUCTION

With reference to moisture damage, pavement construction (including compaction cracks, and air voids content) is a major factor affecting the performance of the laid asphalt pavement. As mentioned in the literature review, different types of explanations have been provided to justify the influence of pavement compaction on stripping (Hicks 1991, Mohamed et al 1993, Terrel and Al-Swailmi, 1993). The first explanation refers to the role of in-place air voids content as a main factors that influence of pavement compaction on stripping. Another explanation relates to surface hairline construction-induced cracks that are caused by conventional steel drum rollers (Mostafa and Abd El Halim 2004, Mohamed et al. 1992, Abd El Halim, 1986, 1989, 1989, and Abd El Halim et al 1987). Furthermore, the over-riding aspect affecting construction appears to be permeability (air voids and hairline cracks), which refers to the theory that permeable material may have a shorter life span, compared to impermeable material (Brown et al 1999). Moreover, permeable pavements cause excessive oxidation of the asphalt binder, which in turn, leads to a brittle binder and an increase in pavement cracks (Mack 1964).

The permeability in this context is defined as the ability of a material (asphalt layer) to transmit fluids (water) through its pores when subjected to pressure. Factors that can affect the permeability of HMA pavements have been highlighted in the literature review. These factors are air voids content, layer thickness, asphalt content, NMAS, temperature, aggregate gradation, and voids in mineral aggregate. Therefore, the main

objective of this phase is to examine the relationship between permeability and asphalt mix characteristics.

6.2 METHODOLOGY

The research methodology applied here is illustrated in Figure (6-1) and consists of a laboratory pilot study stage and a field investigation stage. The objective of the laboratory stage was to examine the relationship between permeability and air voids content of the laid asphalt pavement, while the field measurements stage was intended to develop a relationship between permeability and mix characteristics. The permeability of four asphalt mixes was measured in the laboratory, while ten sites were selected for the placement of the permeability measurements for the field-testing stage. For each of these tested sites, three permeability measurements were used on average. In addition, cores were extracted from the laboratory slabs and field sites in order to examine their susceptibility to stripping during the verification stage.

Based on the literature review, both stages used the falling head device to record the drop in water level in the standpipe over encoded time interval (Cooley and Brown 2000). The standpipe was filled up to a specific mark and the drop in water was noted for a certain period (one to two minutes). If the pavement was highly permeable, the time it took to drop a specific interval was recorded. Figure (6-2) shows the permeameter that was used during this investigation. The permeameter is divided into four levels; from the top to the bottom, the first level was filled when the asphalt layer had a low level of

pavement permeability, while the second level was filled when the asphalt pavement mix exhibited a higher level of permeability. For the highly permeable mixes, the permeameter filled up to the top of the second (or third) level and the drop was noted in the second level. Due to the larger diameter of the standpipe, the drop in the level was slow enough to efficiently record the data.

The coefficient of permeability was calculated based on the falling head principal using the following formula:

Equation 6-1: General Form of Falling Head

$$K = (al / At) * \ln\left(\frac{h_1}{h_2}\right)$$

Where:

K = coefficient of permeability (cm/sec).

a = internal cross-sectional area of standpipe, (cm²).

l = thickness of the asphalt layer, (cm).

A = cross-sectional area of the standpipe, (cm²).

t = elapsed time between h₁ and h₂, (sec).

h₁ = initial head, (cm), and

h₂ = final head, (cm).

Figure (6-1): Permeability Testing Program

Figure (6-2): Permeability Equipment "Permeameter"

6.3 LABORATORY TESTING PROGRAM AND RESULTS

6.3.1 Testing Procedure

The main objective of the laboratory pilot investigation was to develop a relationship between the air voids content and permeability. To achieve this objective, four mixes were selected to be examined in the laboratory (Mix 1, Mix 2, Mix 4, and Mix

5). Three sets of slabs were prepared in the laboratory using a vibratory compactor and each set of mixes consisted of three slabs with different compaction efforts (no compaction, medium compaction, and high compaction). The selected mixes included Mix 4, which is known to be susceptible to stripping, while Mix 5 is similar to Mix 4, except that an anti-stripping agent was added to the mix. In addition, Mix 1, and Mix 2 have a different asphalt content gradation and are known to be non-susceptible to stripping.

The testing began with a preparation of wooden boxes with two different sizes (35cm x 35cm x 7.5cm and 50cm x 50cm x 7.5cm). The loose mixes were placed into the boxes and compacted to the required level of compaction. The permeability was measured for each set of slabs using the equipment shown in Figure (6-2). During the process of measuring the permeability, it became obvious that the 35cm x 35cm slabs should have been waxed from all sides to ensure that only the vertical permeability would be measured. However, there were no signs of water coming from the side of the 50 cm x 50cm x 7.5cm slabs and the concerns may have been unwarranted. The characteristics of the examined mixes used for the test were presented in chapter 3. A summary of air voids content, BRD, and MRD for each mix type is presented in Table (6-1). The field permeameter shown in Figure (6-2) was used as a falling head device to record the drop in water head at a predetermined time. The permeameter was filled up with water to the top of the "67 cm" marking. As mentioned before, the permeameter is divided into four levels and each level accurately represents a different level of permeability (from the top to the bottom, low permeability to high permeability is simulated).

Three tests were conducted for each slab, and the average of the three measurements was calculated. In addition, six cores were extracted from each mix in order to measure the actual density and the retained strength for each mix. The recorded data was used to examine the relationship between TSR and permeability and all the conducted laboratory measurements were performed at 25 °C. Table (6-2) lists all the required variables affecting the permeability measurements. The relationship between these variables and the permeability will be analyzed in the next section. It is recommended, based on practical experience, to observe the permeameter for five minutes prior to taking any readings to decide which level will be used to measure the permeability. However, in case of a highly permeable mix, the reading needs to be taken faster, which is not the case for most dense graded asphalt pavement mixes.

Table (6-1): Properties of Laboratory Tested Slabs

Mix Type	Compaction Type	BRD Kg/cm ³	MRD Kg/cm ³	Air Voids %
Mix1	Low	2.20	2.48	11.34
	Medium	2.35	2.48	5.40
	Fair	2.41	2.48	3.02
Mix2	Low	2.17	2.48	12.31
	Medium	2.30	2.48	7.14
	Fair	2.38	2.48	3.84
Mix4	Low	1.95	2.44	20.05
	Medium	2.16	2.44	11.28
	Fair	2.27	2.44	7.10
Mix5	Low	2.12	2.44	12.91
	Medium	2.28	2.44	6.43
	Fair	2.33	2.44	4.48

Table (6-2): Permeability Measurements for Laboratory Tested Slabs

Mix	Compaction	Thickness	Air Voids	AC	NMAS	VMA	K
		cm	%	%	mm	%	cm/sec *10 ⁻⁴
Mix1	Low	7.5	11.34	5.79	9.6	15.2	104.90973
	Medium	7.5	5.40				8.40017
	Fair	6.5	3.02				0.58452
Mix2	Low	7.5	12.31	6.06	9.6	15.2	117.56728
	Medium	7.5	7.14				15.36426
	Fair	7	3.84				0.99056
Mix4	Low	7.5	20.05	6.10	4.75	15.3	570.46392
	Medium	7.5	11.28				106.12688
	Fair	6.5	7.10				4.12970
Mix5	Low	7.5	12.91	6.10	4.75	15.3	92.14913
	Medium	7.0	6.43				7.78557
	Fair	7.0	4.48				0.43779

6.3.2 Analysis of Laboratory Investigation

The objective of the analysis of the laboratory results is to examine the relationship between permeability and air voids, and to define the factors that might affect the permeability.

Many trials were carried out using the regression analysis technique to determine the best model that can represent the relationship between the permeability and air voids content. The power and/or exponential models were able to represent the best fit for the data. However, only the power relationships are presented here because they have higher R^2 values. The obtained models were significant at a 95 % level of confidence with R^2 ranging from 0.91 to 0.99. Figures (6-3), (6-4), (6-5), and (6-6) show the trend of each mix, while Table (6-3) lists the summary of the derived models. Figure (6-3) shows the

relationship between the permeability coefficient and air voids content in percent for Mix 1. It is seen from that figure that the permeability coefficient increases with the air voids content since the degree of correlation R^2 is found to be 0.992. Similar to Figure (6-3), Figure (6-4) illustrates that permeability increases with air voids content for mix 2 and it gives R^2 of 0.997. The same conclusion can be drawn for Figures (6-5) and (6-6) with different R^2 values. For all mixes, it seems that when the air voids pass a certain value, the permeability increases significantly and becomes very sensitive to a change in air voids content.

The pilot study aimed to investigate the nature of the relationship between air voids content and permeability for the pavement, and the statistical analysis showed that they are highly correlated. Therefore, the air voids should be considered as a main parameter when the relationship between permeability and mix characteristics will be developed after conducting the field measurements.

Figure (6-3): Air Voids and Permeability Coefficient Trend for Mix 1

Figure (6-4): Air Voids and Permeability Coefficient Trend for Mix 2.

Figure (6-5): Air Voids and Permeability Coefficient Trend for Mix4

Figure (6-6): Air Voids and Permeability Coefficient Trend for Mix 5.

Table (6-3): Summary of the pilot Investigation Models

	Equation	R ²
Mix1	$Y=0.00909 X^{3.89690}$	0.992
Mix2	$Y=0.00421 X^{4.10520}$	0.997
Mix4	$Y=0.00054 X^{4.72947}$	0.930
Mix5	$Y=0.00031 X^{5.03761}$	0.912

The second objective of this pilot investigation was to redefine the factors that affect permeability in order to obtain a higher degree of freedom and a more describable variable. The redefined variable can be used to explain the relationship between permeability and mix characteristics. The following variables were considered during the analysis:

- K = hydraulic conductivity (permeability)
- Av = air voids content
- AC/VMA = the ratio between asphalt content and the volume of mineral aggregate
- T/NMAS = the ratio of layer thickness and Nominal Maximum Aggregate Size.

Both, the permeability factor and the air voids content remained the same, whereas the ratio between the asphalt content and the voids in the mineral aggregate was calculated as an indicator of the quality of coating. As mentioned in the literature review with respect to stripping mechanisms, the probability of moisture-induced damage is less

if a better asphalt coating is produced. In addition, the ratio between the layer thickness and NMA represents the structure of the mix. Therefore, it is expected that when the air voids content increases, the permeability increase, while when AC/VMA and/or T/NMA increase the permeability decreases.

6.4 FIELD INVESTIGATION

6.4.1 Site Selection

Field work began with the selection of locations for the investigation and four sites at the National Research Council "NRC" were selected. These sites include susceptible and non-susceptible asphalt mixes. In addition, two types of compaction methods were chosen, including the conventional steel drum roller and AMIR roller. In addition, six sites from the newly laid asphalt pavement mixes were selected: two from the City of Ottawa, and four test sites from the Lafarge Construction Company. The specifications of the used mixes are shown in detail in Appendix 6.

6.4.2 The Testing program

The available data were collected for each site, which includes data from the asphalt content (AC), gradation, NMA, layer thickness (T), voids in mineral aggregate (VMA), and air voids content (Av). Moreover, the permeability was measured using the permeameter shown in Figure (6-2).

In addition, a minimum of six cores were extracted from each site to evaluate the susceptibility of these mixes (sites) to the moisture-induced damage in the laboratory. The results of the latest evaluation will be used to assess the relationship between permeability and retained strength (stripping), and to verify the laboratory-developed guidelines.

6.5 RESULTS AND ANALYSIS

Permeability tests were conducted in the field for different mixes using the permeameter device. The analysis of the results was carried out to identify the significant factors that affect the permeability of dense-graded hot mix asphalt "HMA". During field tests, the asphalt concrete surface layer permeability, as a function of the hydraulic conductivity (k), was determined for the constructed pavement sections using AMIR roller and conventional steel drum roller, respectively. The permeability was measured at different locations that were compacted by the steel drum or AMIR compactor.

6.5.1 National Research Council (NRC) Test Site - 1990

The first test, which was conducted at the National Research Council (NRC) test site, involved the compaction of an HL-3 asphalt mix. In total, twelve pavement specimens were obtained from asphalt compacted by the AMIR roller and the steel-drum roller. The average values of the hydraulic conductivity for the specimens compacted by AMIR and the steel drum roller were 3.797×10^{-5} cm/sec and 42.767×10^{-5} cm/sec, respectively. The HL-3 asphalt mix compacted by the AMIR roller was found to be more

than 11 times less permeable than the same mix compacted by the steel drum roller. The hydraulic conductivity results of the NRC tests for asphalt samples compacted by AMIR and the steel-drum roller are listed in Table (6-4). In addition, the permeability was measured for two additional sites at the NRC; the two sites were compacted using the steel compactor for mix HL4 with and without an anti-stripping agent. As can be seen in Table (6-4), the HL4 mix without an anti-stripping agent had an average permeability coefficient K of 22.00×10^{-5} cm/sec while the same mix with an anti-stripping agent had a lower K value of 1.16×10^{-5} cm/sec which means that anti-stripping agents reduce the permeability by nineteen times its original value. The mix characteristics and the measured permeability values are presented in Table (6-4).

6.5.2 Moodie Drive Test Site - 2003

The second test, which was conducted at Moodie Drive in the month of November 2003, involved the compaction of an HL-3 asphalt mix. In total, twelve pavement specimens were obtained from asphalt compacted by the AMIR roller and the steel-drum roller. The average values of hydraulic conductivity for specimens compacted by the AMIR and the steel drum roller were 8.5×10^{-6} cm/sec and 111.0×10^{-6} cm/sec, respectively. The HL-3 asphalt mix compacted by the AMIR roller was found to be 13.1 times less permeable than the same mix compacted by the steel drum roller. The Moodie Drive test results of the comparison of the hydraulic conductivity of asphalt samples compacted by AMIR and the steel-drum roller, are listed in Table (6-5).

6.5.3 Micro-surfacing sites - 2004

Two sites were selected from the newly laid asphalt in the city of Ottawa; and the selected two sites featured a 0.5 cm thickness of micro surfacing to increase the friction. The investigation of those two sites aimed to identify the effect of micro surfacing on the permeability of the tested sites. The laid mix for both sites was HL3 (which is a common municipal mix). The mix design and the micro-surfacing specifications can be seen in Appendix 6, while the permeability measurements are listed in Table (6-5). The average values of hydraulic conductivity for specimens with micro-surfacing at the Prince of Wales site was 2.2×10^{-6} cm/sec, while they were 1.97×10^{-6} cm/sec for Hunt club site. Both of these sites feature heavy traffic and therefore the measurement procedure required a significant amount of time. However, only the spots with micro-surfacing were measured, which are located at the intersections. Although the research required measuring the permeability for the same mixes without micro surfacing; comparing the results of these two sites with any of the sites without micro-surfacing for the same mix (Moodie Drive) proved that micro-surfacing reduced permeability. However, these results require more investigation.

6.5.4 Orleans Test Site- 2004

The third test, which was conducted in Orleans in the month of September 2004, involved the compaction of an HL-3 asphalt mix. In total, twelve pavement specimens were obtained from asphalt compacted by both, the AMIR roller and the steel-drum

roller. The average values of the hydraulic conductivity of the specimens compacted by AMIR and the steel drum roller were 4.48×10^{-5} cm/sec and 3.44×10^{-4} cm/sec, respectively. The HL-3 asphalt mix compacted by the AMIR roller was found to be 7.7 times less permeable than the same mix compacted by the steel drum roller. The results of the Orleans tests comparing the hydraulic conductivity of asphalt samples compacted by AMIR and the steel-drum roller are summarized in Table (6-5). The asphalt specimens (HL3 mix) compacted by the AMIR roller had a lower hydraulic conductivity than those compacted by the conventional steel-drum roller. Asphalt concrete pavements compacted by the steel-drum roller were found to be up to 13 times more permeable than those compacted by the AMIR roller.

6.6 GENERAL OBSERVATIONS

The results shown in Table (6-4) and (6-5) proved that the asphalt layers which were compacted using the AMIR compactor was, in average, ten times less permeable than the asphalt layers compacted using the steel drum compactor despite the location, which means that the mixes compacted by AMIR will have a longer life time. In addition, the variation from one site to another could be due to a different mix design (Appendix 6), gradation, asphalt content, as well as the quality of the compaction. Furthermore, the micro surfacing does affect the permeability, but more sites are required in order to quantify the reduction in the permeability. The difference in the measured permeability due to the use of the anti-stripping agents was about nineteen times less than without the

anti-stripping. This latest observation leads to the conclusion that the AMIR compactor may produce the same effect as the anti-stripping agent, since it reduces the permeability by an average of ten times. Finally, the difference between the Moodie Drive location and the Orleans location for the same mix (HL-3) might be due to the difference in the ratio of the (AC/VMA) which is higher for the Moodie Drive location.

Table (6-4): Summary of the Measurements of the National Research Council Sections

Mix	Equipment	Agents	Thickness	AV %	AC %	VMA	NMAAS mm	K
			cm			%		cm/sec 10^{-4}
HL-3	AMIR	NO	6.24	4.99	5.1	14.5	9.6	0.373
	AMIR		6.28	4.84				0.437
	AMIR		6.20	5.14				0.325
HL-3	STEEL	NO	6.49	6.15	5.1	14.5	9.6	3.010
	STEEL		6.40	6.10				4.840
	STEEL		6.34	6.05				4.980
HL-4	STEEL	NO	4.30	4.40	5.5	15.3	13.2	2.160
	STEEL		4.35	4.30				2.040
	STEEL		4.45	4.50				2.400
HL-4	STEEL	YES	6.28	3.75	5.5	15.3	13.2	0.086
	STEEL		6.10	3.81				0.115
	STEEL		6.18	3.84				0.147

Table (6-5): Summary of the Measurements of the Lafarge and City of Ottawa Sites

Mix	Equipment	Site	Thickness	AV	AC	VMA	NMAS	K
			cm	%	%	g	mm	cm/sec 10 ⁻⁴
HL-3	STEEL	Prince of Wales With Micro Surfacing	5.05	3.70	5.1	14.8	9.6	0.021600
	STEEL		5.05	3.65				0.027500
	STEEL		5.10	3.85				0.019300
HL-3	STEEL	Hunt Club Micro Surfacing	5.35	3.10	5.2	14.6	9.6	0.005985
	STEEL		5.15	3.07				0.008740
	STEEL		5.10	3.00				0.044500
HL-3	AMIR	Lafarge Moodie	5.04	4.00	5.0	13.1	9.6	0.115000
	AMIR		5.19	4.00				0.112000
	AMIR		5.24	4.12				0.028000
HL-3	STEEL	Lafarge Moodie	4.89	7.30	5.0	13.1	9.6	1.200000
	STEEL		5.97	7.55				9.210000
	STEEL		4.89	7.40				1.220000
HL-3	AMIR	Lafarge Orleans	5.0	5.00	5.3	15.3	9.6	0.383000
	AMIR		5.2	5.12				0.574000
	AMIR		5.1	5.03				0.384000
HL-3	STEEL	Lafarge Orleans	5.29	5.98	5.3	15.3	9.6	4.940000
	STEEL		5.19	5.90				3.470000
	STEEL		5.09	5.85				1.920000

The analysis of the field measurements was carried out in two steps. The first step entailed the analysis of the data through observation, while the second step used the regression analysis to develop a model that accommodates the factors that affect permeability.

As the pilot investigation had indicated, the collected data illustrated that as the in-place air voids increased, the permeability increased. The field data observations showed that the permeability of the investigated sites increased to above 5% when the air voids content increased.

The selected variables for the regression analysis were the compaction type (Steel or AMIR), NMAS, AC, air voids content (A_v), and layer thickness (T). The permeability was tested at different times; beginning in July 2003 at the Moodie Drive location, then in July 2004 at the NRC location, and the final test was completed in September 2004 in Orleans. Since the collected data from the steel compactor sites was treated independently from the data collected from the AMIR sites, two separate models were produced. Moreover, to reduce the number of independent variables, the analysis considered the same factors that were redefined during the laboratory pilot study, including permeability, air voids (A_v), (AC/VMA), and ($T/NMAS$). Modeling the relationship between the permeability coefficient " K " and the above mentioned variables began with a linear regression. However, this trial failed because the distribution of the collected data was not normal. As has previously been discussed, the relationship between air voids and permeability coefficient was found to be powered (or exponential). Therefore, a nonlinear regression was applied to determine the relationship between the

permeability and air voids content. Unlike the traditional linear regression, the nonlinear regression can estimate models with arbitrary relationships between the independent and dependent variables. This is accomplished using iterative estimation algorithms. Therefore, the algorithm used during this analysis was the Levenberg-Marquardt algorithm. The Levenberg-Marquardt algorithm can be thought of as a trust-region modification of the Gauss-Newton algorithm.

The Curve Estimation procedure was used to identify useful functional relations between the dependent variable and each independent variable separately. The results of the Curve Estimation procedure gives relatively high R^2 values for linear and exponential, which means that a number of alternatives should be considered for each model. Therefore, based on the Curve Estimation procedure, the second trial was developed using the non-linear regression technique, using the general form presented in equation 6.2, the resulting model is shown in equation 6.3.

Equation 6-2: General Form for the Relationship between Permeability and Mixes Characteristics

$$K = C + A1 * \text{Exp}(B1 * A_v) + A2 * (T/NMAS) + A3 * (AC/VMA)$$

Equation 6-3: Permeability and Mixes Characteristics Combined relationship

$$K = -1.57E-6 + 0.0000163 \text{Exp}(0.574 * A_v) + 0.000016(T/NMAS) - 0.000496 * (AC/VMA)$$

Where:

K = the hydraulic conductivity, (cm/sec)

A_v = air voids content, (%),

T = layer thickness, (mm),

NMAS = Nominal Maximum Aggregate Size, (mm),

AC = Asphalt Content, (%), and,

VMA = Void in Mineral Aggregate, (%).

The problem with the derived model was that the permeability increased when the ratio (T/NMAS) increased, which was not a logical conclusion. Also, the correlation between the independent factor ratios (T/NMAS) and (AS/VMA) was very high, which was not acceptable. Therefore, the (T/NMAS) ratio was eliminated from the model. However, the resulting model shown in equation 6.4 gave an illogic sign for the ratio of (AC/VMA) and this sign indicated that the permeability increased with an increase in the ratio of the (AC/VMA). The resulting model is represented by:

Equation 6-4: Relationship between Permeability and the Ratio of Air voids content and Voids in Mineral Aggregate

$$K = -0.00096 + 0.0000205 \text{Exp} (0.5543 * A_v) + 0.0024 * (AC/VMA)$$

Finally, the exponential relationship for all independent variables was derived. The developed model is written in the form of an equation 6.5 as:

Equation 6-5: Exponential Relationship between Permeability and the Ratio of Air voids content and Voids in Mineral Aggregate for Steel Compactor

$$K = \text{Exp} [(0.880 * A_v) - (37.100 * (AC/VMA))]$$

The variables are substituted in the equation 6.5, using the following units to determine the permeability in cm/sec. The units of the variables are:

A_v = percentage

AC = percentage

VMA = percentage

The developed model seems logical and very effective with the $R^2 = 0.978$. Moreover, the model seems to be very sensitive to any change in the independent variable. In addition, the final model was compared to the other developed models in which the air voids content was only used as an independent variable. This comparison shows that the air voids content is a dominant factor among the independent variables.

The same concept was used with the AMIR compactor, which resulted in two models written in equations 6.6 and 6.7 respectively. The derived models had high R^2 values of 0.862, and 0.836 and the independent variables had logic signs. The developed model explained that the increase in air voids content increased the permeability coefficient, while the increase in (AC/VMA) and (T/NMAS) ratios decreased the permeability coefficient. The model written in equation (6.7) was compared with the similar model written in equation (6.5) for the steel compactor because both includes the same parameters. Furthermore, equation 6.6 could be used to predict the permeability for AMIR compactor.

Equation 6-6: The Relationship between Permeability and Mixes Characteristics for AMIR

$$K = \text{Exp} [(0.583 * A_v) - (0.125(T/NMAS)) - (35.080 * (AC/VMA))]$$

Equation 6-7: The Relationship between Permeability and Mixes Characteristics for AMIR Compactor

$$K = \text{Exp} [(0.521 * A_v) - (36.151 * (AC/VMA))]$$

6.7 DISCUSSION AND CONCLUSIONS

Based on the laboratory pilot study and the field investigation, the permeability was found to be very strongly related to most of the physical properties of the asphalt pavement mixes. During the laboratory investigation, exponential and power trends were found to have a good explanation for the relationship between the air voids content and the permeability coefficient "K". For the field investigation, more independent variables were entered to the developed models, such as the ratio of asphalt content to voids in mineral aggregate (AC/VMA), and the ratio of asphalt layer thickness to nominal maximum aggregate size (T/NMAS). These variables represented the physical properties and the construction effect of the laid asphalt pavement mix. During this investigation, two main models were developed for two different compactors (conventional steel roller, and AMIR). The permeability model from the obtained data of tested specimens using the AMIR compactor included all the independent variables, while the ratio of (T/NMAS) was removed from the model due to its illogical sign for the collected data of tested specimens using the steel roller compactor.

The developed models could be used to evaluate the quality of the laid asphalt pavement mat based on the actual properties. In addition, based on the developed relationship between air voids content and stripping during phase 3, it is recommended to use the critical air voids content in order to determine the permeability limit, which could be used as a quality assurance of the laid asphalt. Moreover, the permeability values of mixes produced by the AMIR compactor were on average 10 times less than those

produced by the steel drum compactor. This means that the use of the new compaction technology "AMIR" might have a very significant effect on moisture induced damage since it reduces the water flowing through the asphalt. The conclusions of the permeability investigation can be summarized in the following points:

1. Laboratory tests on samples with different compaction show that the change in compaction level can change the air voids content of the prepared samples.
2. Air voids content (measured by voids in the total mix) of dense graded HMA has a significant effect on in place permeability of pavements. It can be considered as the main factor that influences the permeability.
3. There is a significant effect of asphalt content (AC/VMA) on the permeability of HMA. It is shown that the permeability decreases with the increase in asphalt content. Also, the ratio of (T/NMAS) has a significant effect on the permeability.
4. The two similar models derived from the available data are very significant in predicting the permeability using the physical properties of the laid mixes. The steel drum compactor model gives R^2 a value of 0.98, while AMIR compactor gives R^2 a value of 0.86.
5. The mixes compacted by AMIR have less air voids content than those compacted by the conventional roller and they are free of surface cracks. Moreover, the measured permeability of mixes compacted by the steel roller is higher than those compacted by AMIR.

7 VERIFICATION OF THE NEW GUIDELINES

7.1 INTRODUCTION

Both the literature review and the evaluation of the standard test methods reported in chapter 3, highlighted a lack of correlation between the standard test results and the field performance. In addition, the standard test methods have disadvantages that include complexity, reliability and duration. More importantly, current standard tests fail to represent the unique characteristics of the air field asphalt pavement. Therefore, the objective of this research is to replace the existing standard test methods with a new test that is rapid, reliable, correlated to the field, and represents the unique characteristics of Canadian airfield pavements. Moreover, the relationship between permeability and stripping as an overriding factor, while considering the air voids content and surface cracks of laid asphalt pavement mixes, must be examined.

The objectives of this chapter are as follows: First, examine the new guidelines. Second, a critical permeability limit will be determined. Third, the correlation between the permeability measurements and the results of the developed guidelines will be examined. The procedure of the verification starts by comparing the results of the tested samples using the new guidelines with the results of the current standard tests shown in chapter 3. In addition, both results are compared with the obtained airfield results. The comparison includes the results obtained in phase 3 in order to investigate the effect of surface cracks on TSR. Moreover, the correlation between the permeability measurements and the results from the new guidelines are examined. Finally, the

derived permeability models reported in chapter 6 are used to determine the limits in order to evaluate the overall quality of the laid asphalt.

The following will first present the outcomes of the parametric investigation of phases 2 and 3, which will be concluded by a four stage verification procedure. The first stage of the verification procedure will examine the susceptibility of new mixes to moisture-induced damage using the developed guidelines. The second stage will then compare the results of the current standard tests with the results of the developed guidelines. In the third stage of the verification procedure, the ability of the developed guidelines to predict the effect of different compaction levels on moisture-induced damage will be studied. Lastly, the permeability limits and the relationship between the permeability and the TSR will be verified.

7.2 OUTCOMES OF THE PARAMETRIC INVESTIGATION

The parametric investigation includes the assessment of different factors that affect the evaluation of moisture induced damage. During this assessment, different mixes are used to assure that the developed guidelines are valid for a wide range of mixes. The parametric investigation begins with an evaluation of construction effects, including surface cracks and in-place air voids content. Moreover, the conditioning procedures that include the warm water bath duration, temperature and cooling water bath duration are evaluated. In addition, the environmental factors, including freezing thaw cycles and vacuum saturation (degree of saturation), are examined. Finally, the evaluation of the

mechanical properties of the tested samples is carried out, using five different test methods in order to select the most appropriate test method to be used during the evaluation of moisture induced damage. The outcomes of the parametric investigation are summarized in Table (7-1).

Table (7-1): Summary of the Parametric Investigation

Parameter		Result of Investigation	Recommended	Used
Conditioning	Warm Water Bath Duration	Soaking Duration More than 6 hours	(6-10) Hours	6 hours
	Cooling Water Bath Duration	Cooling Duration Between 1 to 2 hours	(1 to 2) Hours	1 hour
Construction	Surface Cracks	Reduce the Laboratory TSR by 10 to 20 %	10 %	10 %
	Air Voids Content	Air Voids ≥ 8 % Soaking Temperature 60 °C	70 °C	70 °C
		Air Voids 3-8% Soaking Temperature 70 °C		
Environmental	Freeze-Thaw Cycles	Random Effect	Optional 2 hours	Not Used
	Vacuum Saturation	Seems to Affect TSR if Degree of Saturation is more than 90%	Optional	
Mechanical Properties	Indirect Tensile Marshall Stability Resilient Modulus Shear Strength Shear Modulus Direct Compression	Marshall Stability	Marshall Stability	Marshall Stability

7.3 VERIFICATION PROCEDURES

The procedure that follows to verify the accuracy of the developed guidelines is divided into four stages. In the first stage, the developed guidelines are used to examine the susceptibility of different mixes. The second stage presents a comparison between the results of the developed guidelines with those of the standard test methods obtained from phase 1 of the research plan during the evaluation of similar mixes (chapter 3). The third stage evaluates the ability of the developed guidelines to predict stripping for different levels of compaction. Finally, the relationship between permeability and stripping is evaluated in the fourth stage.

In the first stage, samples were prepared using six mixes one of them is known to be susceptible to moisture damage. A minimum of six samples were prepared in the laboratory from each mix. In addition, field cores were extracted from two of these mixes to examine the ability of the developed guidelines to correlate laboratory work with field performance. In the second stage, the results obtained during stage 1 of the verification and phase 1 of the research plan were compared to similar mixes. In the third stage, samples from two of the mixes used in the first section were prepared with different air voids content to evaluate the effect of different compaction levels. The loose mix was placed into the oven until it acquired the compaction temperature, then it was placed into 35cm X 35cm forms. The wooden forms were compacted in the laboratory using a vibratory compactor. Moreover, cores were extracted from these slabs and tested for their susceptibility to stripping.

The samples of the fourth stage were extracted from the same sites in the field at which the permeability was measured. During this stage, the ability of the developed guidelines to detect stripping in the field samples was evaluated. In addition, the correlation between permeability and stripping was examined.

In each stage, the prepared samples were divided into groups. Each group from the same mix was divided into two subgroups, assuring the same average density. Then, the new conditioning guidelines were applied as follows:

- Samples were prepared with an air voids content of $\geq 8\%$ and some samples were prepared using the specified mix design air voids content (3 to 5%).
- The conditioned samples were soaked for six hours in a warm water bath at 70°C .
- The samples were cooled for one hour
- The mechanical properties of the tested samples were examined, using the Marshall Stability test for the conditioned and unconditioned sample groups.
- The MSR was calculated.
- The laboratory Obtained MSR was reduced by 10% in order to add the surface cracks effect.
- The results were evaluated, using the PWGSC criteria which accepted the mix giving $\text{MSR} \geq 75\%$.

7.4 RESULTS OF THE VERIFICATION STAGES

7.4.1 Verification Results for Stage 1

The mixes included in this stage were laboratory and field mixes, respectively. The laboratory mixes were Mix1, Mix2, and Mix4 to Mix7, whereas the field mixes were Mix1 and Mix2. The physical properties of these mixes were presented in chapter 3 (cf. Tables (3-1) and (3-2), while the other properties of the mixes are presented in Appendix 7. The results of the evaluation of these mixes using the developed guidelines are presented in Table (7-2). The obtained results showed that the developed guidelines were able to predict the strippable mix. The Marshall Stability Ratio (retained strength) for the susceptible mix "Mix4" was 72.7%, while the retained strength of Mix 5 (prepared with an anti-stripping agent) was 88.9 %. In addition, the results showed that the non-cracked field samples from Mixes 1 and 2 had retained strengths of 80.8% and 83.2%, respectively, which were greater than the accepted strength limit of 75% in accordance with PWGSC specifications. Furthermore, mixes 6 and 7, which were not airfield pavements mixes, had retained strengths of 85.2% and 94.5%, respectively. Based on the obtained results, both Mix6 and Mix7 achieved the required MSR (75%), which means that the developed guidelines could also be used to evaluate highway and airfield mixes.

Table (7-2): Marshall Stability (MSR) for samples of stage one.

Tensile Strength	Mix1	Mix2	Mix1	Mix2	Mix4	Mix5	Mix6	Mix7
	Laboratory		Field		Lab	Lab	Lab	Lab
Dry Samples (N)	49644	47694	30516	25945	41934	36335	22953	34373
Conditioned Samples (N)	44125	44011	23528	20733	30482	32307	19556	32622
Retained Strength (MSR) (%)	88.9	92.3	80.8	83.2	72.7	88.9	85.2	94.5
Final MSR	78.9	82.3	80.8	83.2	62.7*	78.9	75.2	84.5

Interestingly, Mix 4, which was known to be susceptible to stripping, had a retained strength of 72.7 %. Considering the field construction effect (surface cracks, and air voids content), the retained strength value was reduced to 62.7 %, which show that Mix4 failed according to the PWGSC criteria (i.e. it requires a retained strength of 75%). Moreover, when the same procedure was used to evaluate Mix 5, the value of the retained strength was 78.9%, which satisfied PWGSC criteria. The results of the laboratory and field prepared samples for Mixes 1 and 2 showed that there was about 10 % difference between them.

7.4.2 Verification Results for Stage 2

The second stage aimed to compare the results of the developed guidelines and the current standard test method results presented in Tables (3-3), and (3-4). Table (7-2) shows the summary of the results for both groups whereas unexpected results are labelled by a star “*”. The Table highlights that two major advantages were achieved by the

newly developed guidelines First the developed guidelines were able to differentiate between the failed mixes, such as Mix4, and the successful mixes. Moreover the field sample results (Mix1 and Mix2) showed that the developed guidelines allowed the mixes to pass the required criteria (PWGSC). In addition, the second advantage was that laboratory and field results were very similar due to the inclusion of the surface cracks effect to the laboratory sample, which means that the correlation between laboratory and field performance is achievable.

Comparing the developed guidelines and the current standard test methods results showed that the PWGSC passed all mixes, including Mix 4, which might be attributed to the warm water bath duration. This investigation showed that soaking the unconditioned samples for 30-40 minutes, reduced the ITS of these samples by at least 30%. In addition, the results in Table (7-2) indicated that the test methods MTO, ASTM, and AASHTO failed to pass Mix 1 and/or Mix2 for both laboratory and field samples. The AASHTO test method passed Mix 4, while it should have failed it. Comparing the results proved that the developed guidelines are more advantageous than the currently used standard test methods. The success of the developed guidelines is mainly due to the test's consideration for construction cracks, which may finally lead to a correlation between laboratory and field performance.

Table (7-3): Results for the Standard Test Methods and the New Test Method.

Test			Mix1	Mix2	Mix4	Mix5
PWGSC (75%)	Lab	MSR	84.3	94.1	94	91
	Field	MSR	82.3	95.9		
MTO (70%)	Lab	MSR	98.5	71.7	71	77
	Field	MSR	64.5*	46.1*		
ASTM (80%)	Lab	TSR	74.3*	70.3*	65	81
	Field	TSR	79.7	63.8*		
AASHTO (80%)	Lab	TSR	79.7	71.07*	86	91
	Field	TSR	85.1	55.3*		
Developed Guidelines	Lab	MSR	88.9	92.3	72.7*	88.9
	Field	MSR	82.6	85.4		

* Failed according to the required criterion for each standard

7.4.3 Verification Results for Stage 3

The objectives of the third stage of the verification process are to investigate the ability of the developed guidelines to identify the effect of different compaction levels of mixes and to examine the effect of different air voids content on their MSR. Three levels of compaction were used. For the first level of compaction, the mixes were loosely placed into a wooden box without any compaction. The second level of compaction aimed to achieve mixes with 10% of in-place air voids, whereas the third level aimed to achieve mixes with an air voids content of 3-5%. The permeability was measured three times for each mix slab. Then, the samples were extracted from these slabs in order to evaluate their susceptibility to moisture-induced damage.

The developed guidelines were applied to examine the susceptibility of the extracted samples to moisture-induced damage considering the in-place air voids content that is shown in Table (7-4). The obtained results in Tables (7-5) and (7-6) proved that the developed guidelines were able to identify the effect of compaction level (air voids content). The comparison between the results of four different mixes illustrated that only Mix 4 was failed in all levels of compaction according to PWGSC ASG 06. The remaining mixes passed for all levels of compaction, except for the first level where the mixes were loose.

So far, the developed guidelines have been able to evaluate the effects of different compaction levels, proving that the air voids content affected the retained strength of the tested samples. The same conclusion has been drawn from Phase 3, indicating that the air voids content should be accurately measured during stripping evaluation of different samples.

Generally, the increase of the air voids content causes a reduction in the MSR. Moreover, comparing the obtained values of the TSR with the relative values of air voids content for Mix1, Mix2, Mix4, and Mix5, it became obvious that an average increase of air voids content by 2%, led to a change of around 6 % in the MSR. Furthermore, the present finding seems compatible with the finding obtained during Phase 2, which stated that air voids content affects the MSR, and both findings could be used to explain the difference between laboratory and field results of Mix1 and Mix 2 shown in Table (7-2).

Table (7-4): Summary of the Air Voids Content for Different Levels of Compaction

Mix	Compaction Level	Average Air Voids Content %
Mix1	Low	11.34
	Medium	5.40
	Fair	3.02
Mix2	Low	12.31
	Medium	7.14
	Fair	3.84
Mix4	Low	20.05
	Medium	11.28
	Fair	7.10
Mix5	Low	12.91
	Medium	6.43
	Fair	4.48

Table (7-5): Summary of the Results for Stage 3.

Mixes	Marshall Stability (N)					
	Mix1			Mix2		
Samples Condition	Dry (1)	Wet (2)	MSR (3)	Dry (1)	Wet (2)	MSR (3)
Low Compaction	16950	12450	73.5	15255	11167	73.2
Medium Compaction	30942	24506	83.2	26921	21112	78.4
High Compaction	49644	44125	88.9	47694	44011	92.3

Table (7-6): Summary of the Results for Stage 3.

Mixes	Marshall Stability (N)					
	Mix4			Mix5		
Samples Condition	Dry (1)	Wet (2)	MSR (3)	Dry (1)	Wet (2)	MSR (3)
Low Compaction	12578	0	0	14855	10167	68.4
Medium Compaction	30942	19607	63.4	27909	23112	82.8
High Compaction	41934	30482	72.7	36335	32307	88.9

7.4.4 Verification Results for Stage 4

The objective of the fourth stage was to verify the developed guidelines using field mixes. To achieve this objective, three test sites were selected, including the National Research Council (NRC), Moodie Drive, and Orleans. For the NRC site, mix HL-3 and HL-4 were tested. Two different compaction methods (AMIR and Steel rollers) were used to prepare mix HL-3. Whereas, mix HL-4 was compacted with and without an anti-stripping agent using the steel drum. Therefore, four different sections were produced. The second test site was newly constructed at Moodie drive; only one mix was used at that site and two sections were produced using different compaction techniques (AMIR and Steel rollers). The last test site was constructed at Orleans where two sections were produced at the second test site. It is important to note that these sites were constructed to investigate the factors that can affect moisture induced damage, including two different compaction methods.

The permeability was measured for these sites and a minimum of six samples were collected from each section to evaluate their susceptibility to stripping. The dimensions and densities were measured for the collected samples. Then, the developed guidelines were applied to examine the susceptibility of the extracted cores to the moisture-induced damage

The results in Table (7-7) confirm that the developed guidelines were able to evaluate the susceptibility of these field samples to moisture induced damage, even for Mix HL-4 without an anti-stripping agent, which failed according to PWGSC limits. In addition, the results showed that the tested samples from the AMIR compactor section

had a higher MSR than those obtained from the steel drum compactor. This was due to the fact that the AMIR sections were free of construction cracks, while the steel drum sections contained construction cracks. The differences between the results of both compactors ranged from 10.75 at the NRC sections to 12.5 at the Orleans section, which is compatible with the recommended reduction of the developed guidelines shown in Table (7-1).

Table (7-7): Verification of the new guidelines for field cores

Mix	Compaction Equipment	Anti-Striping Agents	Dry Sample	Wet Samples	MSR
			Marshall Stability (N)		
HL3 (NRC)	Steel	Yes	34047	29883	87.8
HL3 (NRC)	AMIR	Yes	39803	45017	97.1
HL4 (NRC)	Steel	No	53413	39415	73.8
HL4 (NRC)	Steel	Yes	48935	39236	80.2
HL3-Moodie	Steel	Yes	31912	26551	80.5
HL3-Moodie	AMIR	Yes	41804	40804	92.6
HL3-Orleans	Steel	Yes	38753	32450	78.7
HL3-Orleans	AMIR	Yes	31543	29125	90.3

7.5 CORRELATION BETWEEN PERMEABILITY AND MARSHALL STABILITY RATIO

The following describes the examination of the correlation between the permeability measurements and the MSR for the prepared specimens from the same sites. In order to evaluate the relationship between the permeability and MSR, twelve locations were examined (cf. Table 7-8). The Curve Estimation procedure was used to determine the best relationship between permeability and stripping (MSR). The best model was derived using the regression analysis technique from 11 different regression models (linear, quadratic, exponential, etc). A separate model was derived for each dependent variable. The results for the curve estimation technique showed that a linear relationship could be used, especially after excluding the outliers. Since there were twelve permeability measurements that corresponded to the MSR, the outliers would not exceed 2 of the total measurements (i.e. outliers were less than 20%). The value of R^2 was 0.35 before excluding the outliers and 0.721 after excluding the outliers based on the available data. Then, reliability of the developed relationship was tested. The normality of the used data was examined and the details are shown in Appendix 7. Figure (7-1) presents the relationship that has the higher value of R^2 . In addition, the relationship between both variables was examined using the Bivariate Correlations procedure to compute Pearson's correlation coefficient and the significance levels. As it is commonly known that Pearson's correlation is a measure of linear association where the two variables are examined for their linear correlation. The results show that the MSR decreases with an

increase in the permeability coefficient “K”. It is important to mention that the value of R^2 tends to optimistically estimate when the model fits the population. However, the model usually does not fit the population. Therefore, the adjusted R^2 is an attempt to correct its obtained value which reflects the success of the model fit in the population. Therefore, the obtained R^2 value of 0.721 is adjusted to 0.688.

For each type of compactor used, a relationship between MSR and the permeability is developed. For the steel drum compactor, the developed relationship between MSR and the permeability is represented in equation 7.2 with R^2 value of 0.65 and adjusted R^2 value of 0.580. The Equation 7.2 is written as:

Equation 7-1: Relationship between Permeability and Marshall Stability Ratio for AMIR Compactor

$$MSR_{AMIR} = 93.719 - 4.6945 (K)$$

Equation 7-2: Relationship between Permeability and Marshall Stability Ratio for the Steel Compactor

$$MSR_{steel} = 91.112 - 3.9586 (K)$$

Table (7-8): Summary of the Permeability Coefficients and their Corresponding MSR.

Mix	Compactions	Location	"K" [Cm/sec] x 10 ⁻⁴	MSR [%]
1	Vibratory	Ottawa Airport	0.58	88.9
2	Vibratory	Ottawa Airport	0.99	92.3
4	Vibratory	Penticton Airport	4.13	72.7
5	Vibratory	Penticton Airport	0.44	88.9
HL3	AMIR	NRC	0.38	97.1
HL3	Steel	NRC	4.28	87.8
HL4	Steel	NRC	2.2	73.8
HL4	Steel	NRC	0.12	80.2
HL3	AMIR	Moodie Dr.	0.85	92.6
HL3	Steel	Moodie Dr.	3.88	80.5
HL3	AMIR	Orleans	0.45	90.3
HL3	Steel	Orleans	3.44	78.7

Figure (7-1): The relationship between MSR and Permeability

7.6 CALCULATING FIELD PERMEABILITY LIMITS

One of the main objectives of this research was to develop a non-destructive quality assurance tool, which could be used to evaluate the overall quality of the laid asphalt pavement mixes. Two different methods of calculation were used to determine the permeability limits and the results were compared. The first method was based on the critical air voids content obtained from phase 2, in conjunction with the permeability models developed in chapter 6. The second method depended on the use of the developed relationship between permeability and stripping.

7.6.1 Critical Air Voids Content

The concept used to determine the critical permeability limit was based on the developed models during phase 4 and the critical air voids value obtained from phase 2. The critical air voids content value ranged from 7.4 % to 8.6 % with a soaking temperature of 60 °C. It was preferred to use the range of air voids content between 7.4% up to 8.6%, since this range could be applied with average values of (AC/VMA) and (T/NMAS). One model was developed for each compactor type (AMIR and Steel Roller). These models were represented in equations 6.5 and 6.7, respectively. The permeability critical limits were calculated using both equations for the valid range of critical air voids content based on the obtained critical air voids content during phase 2. In addition, the other independent variables were based on the properties of airfield asphalt pavement mixes.

$$K_{\text{steel}} = \text{Exp} [(0.880 * A_v) - (37.100 * (AC/VMA))]$$

$$K_{\text{AMIR}} = \text{Exp} [(0.521 * A_v) - (36.151 * (AC/VMA))]$$

The previously determined critical air voids content and average value of AC/VMA (air voids content ranged from 7.4 to 8.6) was substituted in the above-listed equations to calculate the critical permeability limits. It was found that for the steel compactor has an average K value of $20 * 10^{-4}$ cm/sec while AMIR compactor has an average K value of $1.5 * 10^{-4}$ cm/sec.

7.7 RELATIONSHIP BETWEEN MSR AND PERMEABILITY

This method used equations 7.1 and 7.2 to calculate the critical permeability limits and assumed that the Marshall Stability ratio has a value of 75%. The calculated permeability coefficient, according to the PWGSC criteria, was found to be $3.99 * 10^{-4}$ for the model that was developed, regardless of the compaction method, and $4.07 * 10^{-4}$ for the steel compactor model.

Obviously, there was a large difference between the critical permeability limits, which were determined using the relationship between MSR and permeability, with those obtained using the concept of critical air voids content. It was believed that the differences were attributed to the exclusion of the outliers during the development of the relationship between permeability and stripping. Also, the data for two sections (Prince of Wales, and Hunt Club) were used to examine the relationship between permeability and

mix characteristics, since field cores could not be extracted. Therefore, the following is recommended: (1) to extend this research and collect more data for both types of compactors, which will lead to very accurate permeability limits, (2) use $K = 4.07 \times 10^{-4}$ as a permeability limit for the airfield asphalt pavement mixes based on the permeability-stripping relationship.

8 CONCLUSIONS

8.1 SUMMARY

Moisture induced damage is one of the major distresses affecting the long-term performance of asphalt concrete pavements. In addition, the current standard test methods utilized to evaluate stripping are neither reliable nor correlated to the field performance. Also, most of the current research in the area of moisture induced damage of asphalt mixes is concentrated on highway mixes with very little, if any, is directed toward airfield mixes. The research work described in this thesis, organized and presented in eight chapters, aimed to develop guidelines for a new reliable test method that is able to determine the degree of susceptibility of airfield asphalt pavement mixes to moisture-induced damage. In addition, the research examined the relationship between permeability and stripping in order to develop a non-destructive test as a quality assurance tool. The main objectives of this research were:

1. To investigate and define the actual causes of the problem of moisture induced damage, specifically with regards to airfield mixes.
2. To determine the main reason for the poor correlation between laboratory results and field performance for moisture induced damage.
3. To develop guidelines for a reliable test method that could be used to evaluate moisture susceptibility of airfield asphalt mixes.

4. To examine the relationship between permeability and the characteristics of the laid asphalt mat.
5. To assess the relationship between permeability of in-service pavements and their susceptibility to stripping.

In order to meet these objectives, five phases of comprehensive experimental and analytical investigations, including field and laboratory testing programs, were performed. The laboratory experimental program, beginning with phase 1, evaluated the current standard test methods using five different airfield mixes, including one known to be susceptible to stripping. In total, 130 laboratory samples from five different mixes and 52 field cores from two mixes were used. The findings of this phase concluded that the evaluated standards are neither reliable nor correlated to the field, which confirms the results of the literature review. Furthermore, it can be concluded that it is of extreme importance to develop new guidelines that are capable of predicting stripping for airfield asphalt pavements.

The parametric investigation in phase 2 investigated the effects of different factors on the evaluation of moisture-induced damage. Seven different mix types and a total of 551 samples were used during this assessment in order to assure that the developed guidelines are valid for a wide range of mixes. The parametric investigation began with an evaluation of construction effects, including surface cracks and in-place air voids content. The conditioning procedure was evaluated by studying the warm water bath duration and temperature, as well as the cooling water bath duration. Finally, the environmental

factors, including freezing thaw cycles and vacuum saturation (degree of saturation), were examined.

Phase 3 investigated the ability of the different test methods to examine the mechanical properties of the strippable material and a total of five mixes and 120 samples were examined. The investigation aimed to select the most appropriate test method that was able to differentiate between strippable and non-strippable mixes. A summary of the outcomes of Phase 2 and 3 is presented in Table (8-1).

In the fourth phase of this analysis, an investigation of the relationship between permeability and the various factors affecting it was carried out. A total of 10 sites were selected for the field permeability measurements and three different types of mixes were completed in the laboratory. In addition, 60 samples were extracted from the field.

Phase 5 carried out the verification of the developed guidelines and a total of 12 mixes and 120 samples were examined. Moreover, permeability limits were calculated to evaluate the overall quality of the laid asphalt pavement mixes.

The comparison between the current standards and the developed guidelines is represented in Table (8-2), where the evaluated parameters of this research are compared with the currently existing standards. In general, the produced guidelines are simple, reliable, and the results of the laboratory tests have shown to be similar to the field tests, after the surface cracks effect was added. The new guidelines have the advantage of being fast (8 hours), correlated to the field through the use of the surface cracks effects and the preparation of the samples with an air voids content of 9.0% ($\pm$). In addition, the

guidelines found that the Marshall Stability test method is more acceptable than any other test method.

Table (8-1): Summary of the Parametric Investigation

Parameter		Result of Investigation	Recommended
Conditioning	Warm Water Bath Duration	Soaking Duration More than 6 hours	(6-10) Hours
	Cooling Water Bath Duration	Cooling Duration Between 1 to 2 hours	(1 to 2) Hours
Construction	Surface Cracks	Reduce the Laboratory TSR by 10 to 24 %	10 to 20 %
	Air Voids Content	Air Voids ≥ 8 % Soaking Temperature 70 °C	70 °C
Environmental	Freeze-Thaw Cycles	Random Effect	Optional 2 hours
	Vacuum Saturation	Seems to Affect TSR if Degree of Saturation is more than 90%	70 % Optional
Mechanical Properties	Indirect Tensile Marshall Stability Resilient Modulus Shear Strength Shear Modulus Direct Compression	Resilient Modulus Marshall Stability	Both

Identifying the quality assurance tool to evaluate the overall quality of the laid asphalt pavement was another objective of this research. It was found that permeability and MSR have a relationship, which was used to develop a field guideline that could be used as a field quality assurance tool.

Table (8-2): Comparison between the Current Standards and the Developed Guidelines

Mix	AASHTO	ASTM	MTO	PWGSC	NEW
Duration	More than 72 hours	48 hours	More than 24 hours	24 hours	8 hours
Air voids content	Required	Required	Required	Not required	Required
Surface Cracks	Not considered	Not considered	Not considered	Not considered	Considered
Vacuum	Required	Required	Required	Not required	Optional
Freezing Thaw	Optional	Required	Required	Not required	Optional
Simplicity	Complex	Medium complexity	Medium complexity	Simple	Simple
Mechanical properties	ITS	ITS	MSR	MSR	MSR
Current evaluation	Failed	Failed	Failed	Failed	Pass

8.2 CONCLUSIONS

The results and analysis carried out in this research support the following conclusions:

1. The problem of moisture-induced damage is a complex phenomenon whether it relates to highway or airfield asphalt mixes. The lack of research in the airfield mixes resulted in the need to initiate this research.
2. The test methods evaluated during this study showed very little consistency and/or correlation with each other. Another obvious weakness is the poor correlation between laboratory and field test results.
3. Surface cracks were found to affect the ITS significantly, whereas the conditioning process did not significantly affect the ITS of the cracked samples.
 - a. Comparing laboratory samples and cracked field cores, the reduction in the TSR due to surface cracks for Mix1 ranged from 4.3% to 16.6%, while the range for Mix2 was 3.5% to 62.7%.
 - b. During the comparison between the cracked and none cracked field cores, the average reduction was found to range from -9.5% to 30.1% for Mix1, while the reduction for Mix2 ranged from -12.0 %to 47.7%.
4. Investigating the effect of the loading direction relative to the cracks direction (parallel or perpendicular) on the ITS and the TSR showed that perpendicular loading was found to yield a higher TSR than parallel loading for all cases.

5. Comparing TSR of the laboratory samples and cracked field cores proved that the average reduction in the TSR due to cracks was 14% for Mix 1 and 24% for Mix 2. In addition, comparing cracked and non-cracked field cores confirmed that cracks reduce the TSR by 6 % and 14 % for mixes 1 and 2 respectively.
6. Since the evaluation of stripping is based on laboratory prepared samples; the findings of this section proved that surface cracks is one of the reasons for the lack of correlation between laboratory test methods and field long term performance. Therefore, it is recommended to reduce the laboratory measured TSR by 10 to 20% due to the effect of surface cracks.
7. During the analysis of the soaking duration in the warm water bath it was observed that six hours soaking period is enough to condition the samples.
8. The results show that the average change of the TSR for all mixes between one and two hours of cooling is 1 %. Therefore, it is recommended to use one hour of cooling period.
9. There was no agreement on effect of the environmental factor's on the TSR. However, since this research is dealing with a Canadian climate including freezing winters and hot summers, it is recommend to apply a 2 hour freezing period at -16° C, followed by a six hour warm water bath. In addition, it is recommended to use a degree of saturation at 70%.
10. The proposed guidelines of the testing procedure showed that for effective stripping evaluation the void content should be at least 8.6%; the soaking

duration should not be more than 6 hours in the warm water bath followed by one hour of cooling at 25° C, and testing the samples using Marshall Stability test method.

11. Air voids content (measured by voids in the total mix) of dense graded HMA affect the laboratory and field permeability measurements.
12. There is a major effect of asphalt content (AC/VMA) on the permeability of HMA. It is shown that the permeability decreases with the increase in asphalt content.
13. The two similar models derived from the available data are important in predicting the permeability using the physical properties of the laid mixes. The steel drum compactor model gives R^2 value of 0.98, while AMIR compactor gives R^2 value of 0.86.
14. The mixes compacted by AMIR have less air voids content than those compacted by the conventional roller and they are free of surface cracks. Moreover, the measured permeability of mixes compacted by the steel roller is higher, ten times at minimum, than those compacted by AMIR.
15. Permeability and asphalt mix characteristics were found to be exponentially related. In addition, the models that explained the nature of the relationship were developed for two types of compactors and produced high R^2 values. The developed models related the measured permeability "K" to the air voids content "AV", the asphalt content "AC", and the voids in mineral aggregate "VMA".

16. The critical permeability limits, which are used to evaluate the overall quality of field asphalt pavements, were determined using two different techniques.
17. Permeability and stripping (MSR) were found to be correlated (0.852) at $\alpha = 0.01$.
18. A relationship between permeability and MSR was introduced and could be further developed to provide a non-destructive test for the evaluation of the mixes in the field during construction and/or for long-term performance. The available data showed that a linear relationship was established with an adjusted R^2 value of 0.65.

8.3 FUTURE RESEARCH

The conclusions and main findings of this research have identified a number of issues worth further investigation. The following are the most important:

1. Air voids content plays a major role in affecting the susceptibility of airfield asphalt pavement mixes, therefore, it is recommended to expand the work herein and find the critical air voids content.
2. Quantifying the effect of construction surface cracks on airfield mixes require more investigation, since only two mixes were used during this thesis.
3. Environmental factors still need more investigation using different approach.
4. Verifying the developed guidelines using more susceptible mixes to evaluate their consistency and repeatability.

5. The relationship between permeability and MSR for both types of compactors (AMIR and Steel) requires more test sites to be verified.

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APPENDIX 1

**Transportation Department
Testing Laboratory
MARSHALL STABILITY &
ASPHALT EXTRACTION**

Contractor: Beaver Road Builders 2002 Mix Design
Type of Sample: Mix-1 Supplier: Beaver
Origin of Sample: Bravo and Taxiway Study Date: Dec 10-2002

Chainage	n/a	
Location	n/a	
Recovered Penetration	n/a	
Asphalt content (lgn) %	5.79	
Determination No.	1	2
Sample Density g/cm ³	2.370	2.384
Air voids in total mix %	3.31	3.46
Voids in mineral aggr.	15.10	15.30
Flow index 0.25 mm	6.721	6.644
Marshall Load N	13335	13365

Sieve Size	Cum. Wt. Ret.	Cum. % Ret.	% Passing	Tolerances (%)		JMF (%)
2" 53.0 mm						
1 1/2" 37.5						
1" 26.5						
7/8" 22.4						
3/4" 19.0						
5/8" 16.0	0.0	0.0	100.0	100.0	100.0	100.0
1/2" 13.2	3.6	0.3	99.7	100.0	93.4	98.4
# 4 4.75	562.2	39.3	60.7	65.9	55.9	60.9
2	773.4	54.1	45.9	55.7	46.7	51.2
# 40 0.425	1065.3	74.5	25.5	38.2	31.2	34.7
# 80 0.150	1317.6	92.2	7.8	10.8	5.8	8.3
# 200 0.075	1367.7	95.7	4.3	6.8	2.8	4.8
PAN (TOTAL)	1429.4	1	0			

Remarks: MRD =

Transportation Department
Testing Laboratory
ASPHALT MIX WORK SHEET

1			Flask Number	
2				
1			2	
A ₁	WEIGHT OF COMPACTED SPECIMEN IN AIR		1221.2	1260.4
A ₂	SURFACE DRY WEIGHT OF SPECIMEN AFTER IMMERSION IN WATER		1224.4	1261.8
B ₁	WEIGHT OF COMPACTED SPECIMEN IN WATER		707.7	733.2
B ₂	VOLUME = $A_2 - B_1$		516.7	528.6
C	BULK SPECIFIC GRAVITY = A_1/B_2		2.370	2.384
D	WEIGHT OF FLASK & MIXTURE IN AIR		2209.2	
E	WEIGHT OF FLASK IN AIR		645.7	
F	WEIGHT OF MIXTURE IN AIR = D - E		1563.5	
G	WEIGHT OF FLASK & MIXTURE IN WATER		1498.1	
H	WEIGHT OF FLASK IN WATER		564.2	
I ₁	WEIGHT OF MIXTURE IN WATER = G - H		933.9	
I ₂	VOLUME = $F - I_1$		629.6	
J	MAXIMUM SPECIFIC GRAVITY = F/I_2		2.483	
K	PERCENT VOIDS IN MIXTURE = $((J - C)/J) \times 100$		3.31	3.46
L	V.M.A. = $100 - [C(100 - AC\%)/Gb]$		15.10	15.30
		AC	5.79	
	Average MRD	2.483		
	MARSHALL TEST VALUES	BRIQUETTE NUMBER		
		1	2	3
	STABILITY (DIAL)			225
	TIME (SEC.)			2.99
	N FROM CALIBRATION TABLE			133335
	THICKNESS, mm			62.5
	CORRECTION FACTOR FOR THICKNESS			1.000
	MARSHALL STABILITY = N * CORR. FAC.			13335
	FLOW = $(T/30) - (DIAL/10000) - 0.007$			6.721
				6.644

**Transportation Department
Testing Laboratory
MARSHALL STABILITY &
ASPHALT EXTRACTION**

Contractor: Beaver Road Builders

May 10-2000 Mix Design

Type of Sample: Mix-2

Supplier: Beaver

Origin of Sample: Bravo and Taxiway

Study Date: Dec 10-2002

Chainage	n/a	
Location	n/a	
Recovered Penetration	n/a	
Asphalt content (Ign) %	6.06	
Determination No.	1	2
Sample Density g/cm ³	2.393	2.384
Air voids in total mix %	3.46	0.00
Voids in mineral aggr.	15.10	15.30
Flow index 0.25 mm	6.233	6.133
Marshall Load N	12508	12908

Sieve Size	Cum. Wt. Ret.	Cum. % Ret.	% Passing	Tolerances (%)		JMF (%)
2" 53.0 mm						
1 1/2" 37.5						
1" 26.5						
7/8" 22.4						
3/4" 19.0						
5/8" 16.0	0.0	0.0	100.0	100.0	100.0	100.0
1/2" 13.2	3.8	0.2	99.8	100.0	93.4	98.4
# 4 4.75	661.2	43.2	56.8	65.9	55.9	60.9
2	823.3	53.8	46.2	55.7	46.7	51.2
# 40 0.425	1123.3	73.4	26.6	38.2	31.2	34.7
# 80 0.150	1370.1	89.5	10.5	10.8	5.8	8.3
# 200 0.075	1463.7	95.7	4.3	6.8	2.8	4.8
PAN (TOTAL)	1530.2	1	0			

Remarks: MRD =

Test Lab Eng.:

**Transportation Department
Testing Laboratory
ASPHALT MIX WORK SHEET**

1		Flask Number			
2					
1				2	
A ₁	WEIGHT OF COMPACTED SPECIMEN IN AIR			1221.2	1260.4
A ₂	SURFACE DRY WEIGHT OF SPECIMEN AFTER IMMERSION IN WATER			1232.4	1261.8
B ₁	WEIGHT OF COMPACTED SPECIMEN IN WATER			717.3	733.2
B ₂	VOLUME = A ₂ - B ₁			515.1	528.6
C	BULK SPECIFIC GRAVITY = A ₁ /B ₂			2.393	2.384
D	WEIGHT OF FLASK & MIXTURE IN AIR			2265.3	
E	WEIGHT OF FLASK IN AIR			645.7	
F	WEIGHT OF MIXTURE IN AIR = D - E			1619.6	
G	WEIGHT OF FLASK & MIXTURE IN WATER			1531.9	
H	WEIGHT OF FLASK IN WATER			564.2	
I ₁	WEIGHT OF MIXTURE IN WATER = G - H			967.7	
I ₂	VOLUME = F - I ₁			651.9	
J	MAXIMUM SPECIFIC GRAVITY = F/I ₂			2.484	
K	PERCENT VOIDS IN MIXTURE = ((J - C)/J) N* 100			3.46	
L	V.M.A. = 100 - [C(100- AC%)/Gb]			15.25	15.16
			AC	6.06	
Average MRD		2.484			
MARSHALL TEST VALUES		BRIQUETTE NUMBER			
		1	2	3	4
	STABILITY (DIAL)			225	2.15
	TIME (SEC.)			2.99	2.91
	N FROM CALIBRATION TABLE			12508	12908
	THICKNESS, mm			62.5	62.5
	CORRECTION FACTOR FOR THICKNESS			1.000	1.000
	MARSHALL STABILITY = N * CORR. FAC.			12508	12908
	FLOW = (T/30) - (DIAL/10000) - 0.007			6.233	6.133

**Transportation Department
Testing Laboratory
MARSHALL STABILITY &
ASPHALT EXTRACTION**

Contractor: EBA

Mix4

Type of Sample: Penticton Air port without Anti-Stripping Supplier: EBA

Origin of Sample: Vancouver

Date: April 08-2003

Chainage		
Location	1/1/1	
Recovered Penetration		
Asphalt content (By TRI) %	6.03	
Determination No.	1	2
Sample Density g/cm ³	2.347	2.358
Air voids in total mix %	3.93	3.48
Voids in mineral aggr.	18.91	18.53
Flow index 0.25 mm	7.543	7.617
Marshall Load N	15854	16515

Sieve Size	Cum. Wt. Ret.	Cum. % Ret.	% Passing
2" 53.0 mm			
1 1/2" 37.5			
1" 26.5	0	0.0	100.0
7/8" 22.4			
3/4" 19.0	0.0	0.0	100.0
5/8" 16.0	0.0	0.0	100.0
1/2" 13.2	0.0	0.0	100.0
3/8" 9.5	0.0	0.0	100.0
# 4 4.75	480.2	41.1	58.9
# 8 2.36	635.1	54.4	45.6
# 16 1.18			
# 40	948.3	81.2	18.8
# 50 0.300			
# 80 0.150	1098.3	94.0	6.0
# 200 0.075	1154.3	98.8	1.2
PAN (TOTAL)	1167.9	1	0

Remarks: MRD = 2.443

Test Lab Eng.:

Tested By: Students

Date: April 08-2003

Transportation Department Testing Laboratory ASPHALT MIX WORK SHEET			
Mix4					
1	Link 1/1/1	Flask Number			
2	Link 1/1/2				
3	Link 1/1/3	1	2	3	
A ₁	WEIGHT OF COMPACTED SPECIMEN IN AIR			1221.2	1260.4
A ₂	SURFACE DRY WEIGHT OF SPECIMEN AFTER IMMERSION IN WATER			1235.4	1261.8
B ₁	WEIGHT OF COMPACTED SPECIMEN IN WATER			715.1	727.3
B ₂	VOLUME = $A_2 - B_1$			520.3	534.5
C	BULK SPECIFIC GRAVITY = A_1/B_2			2.347	2.358
D	WEIGHT OF FLASK & MIXTURE IN AIR			2209.2	
E	WEIGHT OF FLASK IN AIR			629.7	
F	WEIGHT OF MIXTURE IN AIR = D - E			1579.5	
G	WEIGHT OF FLASK & MIXTURE IN WATER			1498.1	
H	WEIGHT OF FLASK IN WATER			565.1	
I ₁	WEIGHT OF MIXTURE IN WATER = G - H			933	
I ₂	VOLUME = $F - I_1$			646.5	
J	MAXIMUM SPECIFIC GRAVITY = F/I_2			2.443	
K	PERCENT VOIDS IN MIXTURE = $((J - C)/J) \times 100$			3.93	3.48
L	V.M.A. = $100 - [C(100 - AC\%)/Gb]$			18.91	18.53
				2.720	
				6.03	
Average MRD		2.443			
MARSHALL TEST VALUES		BRIQUETTE NUMBER			
		1	2	3	4
STABILITY (DIAL)				219	235
TIME (SEC.)				3.13	3.20
N FROM CALIBRATION TABLE				14845	15910
THICKNESS, mm				61	62
CORRECTION FACTOR FOR THICKNESS				1.068	1.038
MARSHALL STABILITY = N * CORR. FAC.				15854	16515
FLOW = $(T/30) - (DIAL/10000) - 0.007$				7.543	7.617
April 08-2003					
Student

Transportation Department
Testing Laboratory
MARSHALL STABILITY &
ASPHALT EXTRACTION

Contractor: EBA

Mix5

Type of Sample: Penticton Air port with Anti-Stripping

Supplier: EBA

Origin of Sample: Vancouver

Date: April 08-2003

Chainage		
Location	1/1/1	
Recovered Penetration		
Asphalt content (By TRI) %	6.00	
Determination No.	1	2
Sample Density g/cm ³	2.350	2.349
Air voids in total mix %	3.62	3.66
Voids in mineral aggr.	18.19	18.22
Flow index 0.25 mm	7.183	6.900
Marshall Load N	18936	17848

Sieve Size	Cum. Wt. Ret.	Cum. % Ret.	% Passing
2" 53.0 mm			
1 1/2" 37.5			
1" 26.5	0	0.0	100.0
7/8" 22.4			
3/4" 19.0	0.0	0.0	100.0
5/8" 16.0	0.0	0.0	100.0
1/2" 13.2	0.0	0.0	100.0
3/8" 9.5	0.0	0.0	100.0
# 4 4.75	477.5	41.9	58.1
# 8 2.36	620.6	54.4	45.6
# 16 1.18			
# 40	955.0	83.8	16.2
# 50 0.300			
# 80 0.150	1078.5	94.6	5.4
# 200 0.075	1127.3	98.9	1.1
PAN (TOTAL)	1140.0	1	0

Remarks: MRD = 2.438

Tested By: Students

Test Lab Eng.:

Date: April 08-2003

**Transportation Department
Testing Laboratory
ASPHALT MIX WORK SHEET**

Mix5					
1	Link 1/1/1	Flask Number			
2	Link 1/1/2				
3	Link 1/1/3	1	2	3	
A ₁	WEIGHT OF COMPACTED SPECIMEN IN AIR			1221.2	1260.4
A ₂	SURFACE DRY WEIGHT OF SPECIMEN AFTER IMMERSION IN WATER			1235.4	1261.8
B ₁	WEIGHT OF COMPACTED SPECIMEN IN WATER			715.7	725.2
B ₂	VOLUME = A ₂ - B ₁			519.7	536.6
C	BULK SPECIFIC GRAVITY = A ₁ /B ₂			2.350	2.349
D	WEIGHT OF FLASK & MIXTURE IN AIR			2209.2	
E	WEIGHT OF FLASK IN AIR			625.7	
F	WEIGHT OF MIXTURE IN AIR = D - E			1583.5	
G	WEIGHT OF FLASK & MIXTURE IN WATER			1499.1	
H	WEIGHT OF FLASK IN WATER			565.1	
I ₁	WEIGHT OF MIXTURE IN WATER = G - H			934	
I ₂	VOLUME = F - I ₁			649.5	
J	MAXIMUM SPECIFIC GRAVITY = F/I ₂			2.438	
K	PERCENT VOIDS IN MIXTURE = ((J - C)/J) N* 100			3.62	3.66
L	V.M.A. = 100 - [C(100- AC%)/Gb]			18.19	18.22
				2.700	
				6.00	
Average MRD		2.438			
MARSHALL TEST VALUES		BRIQUETTE NUMBER			
		1	2	3	4
STABILITY (DIAL)				255	240
TIME (SEC.)				3.13	3.00
N FROM CALIBRATION TABLE				17230	16240
THICKNESS, mm				60	60
CORRECTION FACTOR FOR THICKNESS				1.099	1.099
MARSHALL STABILITY = N * CORR. FAC.				18936	17848
FLOW = (T/30) - (DIAL/10000) - 0.007				7.183	6.900
April 08-2003					
Student					

APPENDIX 2

Table (A2-1): The Effect of Number of Blows on Bulk Density for Surface Mix1

Number of Blows	10	20	30	40	50
Average Bulk Density SG (gm/cc)	2.31	2.38	2.41	2.41	2.42
Average Percentage of Air Voids (%)	6.93	4.33	3.12	2.78	2.65

Table (A2-2): The Effect of Number of Blows on Bulk Density for Surface Mix2

Number of Blows	10	20	30	40	50
Average Bulk Density SG (gm/cc)	2.30	2.32	2.37	2.39	2.40
Average Percentage of Air Voids (%)	7.30	6.48	4.25	3.75	3.43

Table (A2-3): The Effect of Number of Blows on Bulk Density for Base Mix3

Number of Blows	10	20	30	40	50
Average Bulk Density SG (gm/cc)	2.30	2.35	2.39	2.40	2.42
Average Percentage of Air Voids (%)	7.09	5.43	3.56	2.75	2.55

Figure (A2-1): Relationship between Number of Blows and Air Voids for Mix1

Figure (A2-2): Relationship between Number of Blows and Air Voids for Mix2

Figure (A2-3): Relationship between Number of Blows and Air Voids for Mix3

Figure (A2-4): Relationship between Number of Blows and Density for Mix1

Figure (A2-5): Relationship between Number of Blows and Density for Mix2

Figure (A2-6): Relationship between Number of Blows and Density for Mix3

Table (A2-5): The Effect of Number of Blows on air voids for Mix4, and 5

Number of Blows	10	15	20	30	40	50
Average Percentage of Air Voids Mix-4	9.9	9.1	8.5	7.7	6.9	6.36
Average Percentage of Air Voids (%) Mix-5	7.5	6.1	5.2	4.7	3.2	3.2

Figure (A2-6): Relationship between Number of Blows and Air Voids for Mix4

Figure (A2-7): Relationship between Number of Blows and Air Voids for Mix5

Table (A2-6): Results of Number of Blows and Degree of Saturation at Different Vacuum Duration for Mix1

Number of Blows	10	20	30	40	50
Degree of Saturation (10MIN)	63.98	51.44	44.47	34.93	33.50
Degree of Saturation (30MIN)	69.67	60.12	60.39	51.26	55.34
Degree of Saturation (60MIN)	82.49	79.63	75.94	63.32	58.07

Table (A2-7): Results of Number of Blows and Degree of Saturation at Different Vacuum Duration for Mix2

Number of Blows	10	20	30	40	50
Degree of Saturation (10MIN)	70.81	70.42	61.78	39.35	38.27
Degree of Saturation (30MIN)	80.25	79.23	73.59	57.01	57.12
Degree of Saturation (60MIN)	82.07	81.51	74.46	60.43	58.85

Table (A2-8): Results of Number of Blows and Degree of Saturation at Different Vacuum Duration for Mix3

Number of Blows	10	20	30	40	50
Degree of Saturation (10MIN)	67.97	64.13	66.65	57.43	52.40
Degree of Saturation (30MIN)	80.49

Figure (A2-8): Relationship between Number of Blows and Degree of Saturation at Different Vacuum Duration for Mix1

Figure (A2-9): Relationship between Number of Blows and Degree of Saturation at Different Vacuum Duration for Mix2

Figure (A2-8): Relationship between Number of Blows and Degree of Saturation at Different Vacuum Duration for Mix3

SURFACE MIX HL1 SAMPLE PROPERTIES LABORATORY SAMPLES

S#	D1	D2	Day	H1	H2	Hav	WD1	WW	WD2	VOLUME	BULK DENSITY	MAX SG	% A V
	mm	mm	mm	mm	mm	mm	gm	gm	gm	cc	gm/cc	gm/cc	
1	101.7	101.7	101.7	62.5	62.7	62.6	1219.5	724.5	1219.9	495.4	2.46	2.48	0.7
2	101.5	101.5	101.5	63.5	63.7	63.6	1236.4	727.4	1236.6	509.2	2.43	2.48	2.1
3	101.8	101.7	101.7	56.6	56.6	56.6	1109.4	654.2	1109.5	455.3	2.44	2.48	1.7
4	101.4	101.7	101.5	65.0	65.3	65.2	1269.3	749.0	1269.9	520.9	2.44	2.48	1.7
5	101.7	101.7	101.7	56.2	56.5	56.4	1089.5	639.9	1089.8	450.0	2.42	2.48	2.4
6	101.7	101.7	101.7	59.4	59.5	59.4	1159.9	685.0	1160.4	475.4	2.44	2.48	1.6
7	101.7	101.7	101.7	59.4	59.4	59.4	1153.5	676.1	1153.5	477.4	2.42	2.48	2.6
8	101.6	101.6	101.6	61.4	61.4	61.4	1197.4	706.1	1197.8	491.6	2.44	2.48	1.8
9	102.0	102.0	102.0	60.7	60.8	60.8	1178.1	691.1	1178.4	487.3	2.42	2.48	2.5
10	101.7	101.7	101.7	60.4	60.4	60.4	1176.2	695.2	1176.7	481.5	2.44	2.48	1.5
11	101.7	101.8	101.7	62.2	62.2	62.2	1206.6	707.9	1206.9	499.0	2.42	2.48	2.5
12	101.6	101.6	101.6	59.7	59.7	59.7	1162.5	685.2	1163.0	477.8	2.43	2.48	1.9
13	101.8	101.8	101.8	55.9	55.9	55.9	1085.4	636.9	1085.9	449.0	2.42	2.48	2.5
14	101.8	101.9	101.8	58.8	58.8	58.8	1128.2	664.2	1129.0	464.8	2.43	2.48	2.1
15	101.4	101.5	101.4	58.5	58.5	58.5	1125.0	657.2	1125.6	468.3	2.40	2.48	3.1
16	101.6	101.7	101.6	58.8	58.9	58.9	1148.4	676.7	1149.2	472.4	2.43	2.48	2.0
17	101.7	101.7	101.7	60.9	60.9	60.9	1175.8	687.6	1176.4	488.8	2.41	2.48	3.0
18	101.8	101.9	101.8	59.9	59.9	59.9	1159.0	680.8	1159.6	478.8	2.42	2.48	2.4
19	101.6	101.7	101.6	62.0	62.0	62.0	1189.0	692.3	1189.4	497.1	2.39	2.48	3.6
20	101.7	101.7	101.7	58.3	58.3	58.3	1135.2	667.8	1135.5	467.6	2.43	2.48	2.1
21	101.8	101.8	101.8	62.1	62.1	62.1	1206.3	706.4	1207.0	500.6	2.41	2.48	2.8
22	101.6	101.6	101.6	58.2	58.3	58.2	1130.1	663.4	1130.3	466.8	2.42	2.48	2.4
23	101.8	101.8	101.8	61.6	61.6	61.6	1186.3	692.5	1186.5	494.0	2.40	2.48	3.2

SURFACE MIX HL1 SAMPLE PROPERTIES LABORATORY SAMPLES

S#	D1	D2	Dav	H1	H2	Hav	WD1	WW	WD2	VOLUME	BULK DENSITY	MAX SG	% A V
	mm	mm	mm	mm	mm	mm	gm	gm	gm	cc	gm/cc	gm/cc	
24	101.7	101.7	101.7	56.9	57.0	56.9	1104.0	648.7	1104.4	455.7	2.42	2.48	2.3
25	101.8	101.8	101.8	58.1	58.1	58.1	1114.7	648.9	1115.3	466.3	2.39	2.48	3.6
26	101.7	101.8	101.7	55.1	55.2	55.1	1071.2	628.4	1071.5	443.2	2.42	2.48	2.5
27	101.7	101.7	101.7	53.4	53.4	53.4	1018.1	590.8	1018.6	427.8	2.38	2.48	4.0
28	101.8	101.7	101.7	61.3	61.3	61.3	1181.8	691.4	1182.2	490.8	2.41	2.48	2.9
29	101.6	101.6	101.6	56.9	56.9	56.9	1074.3	623.1	1075.9	452.8	2.37	2.48	4.3
30	101.6	101.7	101.6	55.6	55.6	55.6	1053.4	610.3	1054.3	444.1	2.37	2.48	4.3
31	101.7	101.7	101.7	59.5	59.4	59.5	1142.6	667.1	1143.1	476.0	2.40	2.48	3.2
32	101.7	101.7	101.7	60.0	61.1	60.5	1185.0	697.8	1185.3	487.5	2.43	2.48	2.0
33	101.6	101.6	101.6	58.1	58.0	58.0	1114.1	651.4	1114.6	463.2	2.41	2.48	3.0
34	101.7	101.7	101.7	55.2	55.4	55.3	1045.4	605.6	1046.3	440.8	2.37	2.48	4.4
35	102.0	102.1	102.0	58.3	58.4	58.4	1125.9	657.3	1126.4	469.1	2.40	2.48	3.2
36	101.8	101.9	101.8	58.2	58.2	58.2	1108.5	644.2	1109.4	465.2	2.38	2.48	3.9
37	101.7	101.7	101.7	58.9	59.0	58.9	1133.1	662.1	1133.6	471.5	2.40	2.48	3.1
38	101.6	101.6	101.6	50.9	50.9	50.9	983.1	577.2	983.7	406.4	2.42	2.48	2.5
39	101.7	101.7	101.7	55.4	55.5	55.5	1049.0	637.1	1080.1	443.0	2.37	2.48	4.5
40	101.7	101.8	101.7	54.9	55.0	55.0	1049.0	611.2	1050.1	438.8	2.39	2.48	3.6
41	101.6	101.7	101.6	63.1	62.9	63.0	1199.3	695.7	1199.8	504.0	2.38	2.48	4.1
42	101.7	101.6	101.6	59.2	59.4	59.3	1139.9	668.7	1140.3	471.6	2.42	2.48	2.5
43	101.4	101.4	101.4	52.0	52.2	52.1	1003.9	588.2	1004.2	416.0	2.41	2.48	2.7
44	101.9	101.9	101.9	53.0	53.3	53.1	1030.4	605.0	1030.7	425.7	2.42	2.48	2.4
45	101.7	101.8	101.7	60.0	60.1	60.1	1149.9	671.6	1150.6	478.9	2.40	2.48	3.2
46	101.6	101.7	101.6	57.6	57.5	57.5	1090.8	635.3	1091.5	456.3	2.39	2.48	3.6

SURFACEMIX HL1 SAMPLE PROPERTIES LABORATORY SAMPLES

S#	D1	D2	Dav	H1	H2	Hav	WD1	WW	WD2	VOLUME	BULK DENSITY	MAX SG	% A V
	mm	mm	mm	mm	mm	mm	gm	gm	gm	cc	gm/cc	gm/cc	
47	101.7	101.6	101.6	51.0	51.3	51.1	984.9	576.0	985.3	409.3	2.41	2.48	3.0
48	101.5	101.6	101.6	52.7	52.6	52.7	1014.1	595.5	1014.3	418.8	2.42	2.48	2.4
49	101.6	101.6	101.6	51.9	52.0	52.0	999.6	585.4	999.9	414.5	2.41	2.48	2.8
50	101.8	101.9	101.8	57.3	57.4	57.3	1106.4	648.7	1106.7	458.0	2.42	2.48	2.6
51	101.8	101.5	101.7	57.3	57.5	57.4	1120.9	661.1	1120.9	459.9	2.44	2.48	1.7
52	101.7	101.8	101.7	57.7	57.5	57.6	1106.2	645.1	1106.4	461.3	2.40	2.48	3.3
53	101.6	101.7	101.6	57.8	57.9	57.8	1106.6	647.0	1106.8	459.8	2.41	2.48	3.0
54	101.8	101.9	101.8	57.6	57.8	57.7	1110.0	645.7	1110.4	464.6	2.39	2.48	3.7
55	101.6	101.7	101.6	53.4	53.6	53.5	1028.2	602.6	1028.2	425.6	2.42	2.48	2.6
56	101.7	101.7	101.7	56.1	56.2	56.1	1075.7	626.5	1076.0	449.5	2.39	2.48	3.5
57	101.7	101.7	101.7	55.1	55.3	55.2	1074.6	633.5	1074.9	441.4	2.43	2.48	1.8
58	101.7	101.7	101.7	56.3	56.5	56.4	1070.3	619.8	1071.0	451.2	2.37	2.48	4.4
59	101.8	101.9	101.8	50.8	50.9	50.8	981.0	573.1	981.2	408.1	2.40	2.48	3.1
60	101.5	101.6	101.5	51.6	52.1	51.9	1008.9	596.5	1009.9	413.4	2.44	2.48	1.6
61	101.6	101.7	101.7	60.0	60.2	60.1	1162.8	680.4	1162.3	481.9	2.41	2.48	2.7
62	101.9	102.0	102.0	63.6	63.8	63.7	1225.9	714.6	1226.0	511.4	2.40	2.48	3.3
63	101.6	101.7	101.7	62.8	62.9	62.9	1212.6	712.0	1212.9	501.0	2.42	2.48	2.4
64	101.8	101.9	101.8	61.5	61.5	61.5	1196.0	704.3	1196.2	491.9	2.43	2.48	2.0
65	101.6	101.7	101.6	54.7	54.9	54.8	1065.0	626.6	1065.1	438.5	2.43	2.48	2.1
66	101.7	101.6	101.6	61.4	61.6	61.5	1197.8	707.2	1197.9	490.7	2.44	2.48	1.6
67	101.7	101.8	101.7	60.8	60.9	60.8	1170.5	683.1	1170.7	487.7	2.40	2.48	3.2
68	101.7	101.7	101.7	56.2	56.3	56.3	1089.3	639.3	1089.7	450.4	2.42	2.48	2.5
69	101.7	101.8	101.7	56.6	56.6	56.6	1090.2	637.0	1090.5	453.5	2.40	2.48	3.1

SURFACE MIX HL1 SAMPLE PROPERTIES LABORATORY SAMPLES

S#	D1	D2	Dav	H1	H2	Hav	WD1	WW	WD2	VOLUME	BULK DENSITY		MAX SG	% A V
	mm	mm	mm	mm	mm	mm	gm	gm	gm	cc	gm/cc	gm/cc	gm/cc	
70	101.6	101.7	101.6	59.4	59.8	59.6	1159.6	684.1	1159.8	475.7	2.44	2.44	2.48	1.7
71	101.8	101.8	101.8	61.6	61.8	61.7	1183.6	689.5	1183.7	494.2	2.39	2.39	2.48	3.4
72	101.6	101.7	101.7	57.4	57.6	57.5	1112.7	653.2	1112.9	459.6	2.42	2.42	2.48	2.4
73	101.8	101.9	101.8	61.5	61.7	61.6	1182.0	686.5	1182.3	495.8	2.38	2.38	2.48	3.9
74	101.7	101.8	101.8	64.3	63.3	63.8	1222.7	714.3	1223.2	509.0	2.40	2.40	2.48	3.1
75	101.7	101.7	101.7	59.7	59.8	59.8	1173.8	686.8	1174.1	487.3	2.41	2.41	2.48	2.9
76	101.6	101.7	101.6	60.4	60.7	60.6	1173.9	690.1	1174.2	484.1	2.42	2.42	2.48	2.2
77	101.8	101.7	101.8	56.6	57.0	56.8	1095.4	640.2	1095.8	455.6	2.40	2.40	2.48	3.1
78	101.6	101.7	101.7	58.3	58.7	58.5	1118.1	656.3	1118.5	462.1	2.42	2.42	2.48	2.4
79	101.6	101.6	101.6	58.3	58.7	58.5	1119.3	652.5	1119.6	467.2	2.40	2.40	2.48	3.4
80	101.7	101.6	101.6	57.3	57.5	57.4	1102.2	643.0	1102.4	459.4	2.40	2.40	2.48	3.3
81	101.7	101.8	101.7	57.0	57.1	57.1	1099.4	644.4	1099.9	455.5	2.41	2.41	2.48	2.7
82	101.9	101.8	101.8	60.6	60.7	60.7	1158.9	673.2	1159.7	486.6	2.38	2.38	2.48	4.0
83	101.8	101.6	101.7	57.6	57.8	57.7	1105.6	643.9	1106.1	462.3	2.39	2.39	2.48	3.6
84	101.6	101.6	101.6	60.2	60.5	60.4	1172.0	690.2	1172.3	482.1	2.43	2.43	2.48	2.0
85	101.6	101.7	101.6	56.5	56.2	56.3	1087.2	637.7	1087.9	450.2	2.41	2.41	2.48	2.6
86	101.7	101.6	101.7	56.1	56.3	56.2	1069.5	618.9	1069.9	451.0	2.37	2.37	2.48	4.4
87	101.5	101.6	101.6	53.9	53.8	53.8	1030.0	600.2	1030.6	430.4	2.39	2.39	2.48	3.5
88	101.7	101.7	101.7	51.7	51.6	51.7	1086.8	633.5	1087.4	454.0	2.39	2.39	2.48	3.5
89	101.6	101.7	101.6	57.4	57.6	57.5	1092.5	635.5	1093.8	458.3	2.38	2.38	2.48	3.9
90	101.7	101.8	101.7	56.6	56.7	56.7	1080.5	630.8	1081.3	450.5	2.40	2.40	2.48	3.3

Filed Samples Mix 1																			
S#	D1	D2	Dav	H1	H2	Hav	WD1	WW	WD2	VOLUME	BULK DENSITY	MAX SG	% A V						
	mm	mm	mm	mm	mm	mm	gm	gm	gm	cc	gm/cc	gm/cc							
1	96.2	96.8	96.5	64.1	64.3	64.2	1105.0	641.3	1105.5	464.2	2.38	2.48	4.0						
2	96.8	96.9	96.9	64.2	64.3	64.2	1098.1	634.0	1098.4	464.5	2.36	2.48	4.7						
3	97.0	97.0	97.0	63.6	63.8	63.7	1090.7	629.7	1091.0	461.3	2.36	2.48	4.7						
4	96.3	96.4	96.3	63.3	64.4	63.9	1090.9	632.2	1091.3	459.1	2.38	2.48	4.2						
5	96.4	96.4	96.4	63.8	64.2	64.0	1101.0	638.2	1101.5	463.3	2.38	2.48	4.2						
6	96.3	96.3	96.3	63.0	63.7	63.4	1087.0	628.6	1087.5	458.9	2.37	2.48	4.5						
7	96.3	96.3	96.3	63.7	64.1	63.9	1090.3	631.2	1091.2	460.0	2.37	2.48	4.4						
19	96.3	96.5	96.4	63.6	63.6	63.6	1085.2	625.3	1086.0	460.7	2.36	2.48	5.0						
20	96.2	96.2	96.2	63.7	63.0	63.4	1066.1	609.7	1067.0	457.3	2.33	2.48	6.0						
21	96.2	96.3	96.2	64.1	64.0	64.1	1092.6	630.3	1093.3	463.0	2.36	2.48	4.9						
11	96.3	96.3	96.3	63.3	62.6	62.9	1087.4	631.8	1088.2	456.4	2.38	2.48	3.9						
12	96.5	96.5	96.5	63.3	63.1	63.2	1084.8	630.4	1085.4	455.0	2.38	2.48	3.9						
13	96.2	96.2	96.2	64.0	63.5	63.7	1075.5	617.6	1076.5	459.0	2.34	2.48	5.5						
14	96.2	96.2	96.2	63.6	64.1	63.8	1085.3	625.4	1085.9	460.6	2.36	2.48	5.0						
15	96.2	96.3	96.2	63.7	62.2	63.0	1074.4	620.5	1075.2	454.8	2.36	2.48	4.7						
16	96.2	96.2	96.2	63.8	63.7	63.7	1085.3	627.4	1086.1	458.7	2.37	2.48	4.6						
17	96.3	96.3	96.3	63.5	62.8	63.2	1084.6	629.8	1085.4	455.6	2.38	2.48	4.0						
18	96.5	96.4	96.4	64.1	62.4	63.3	1082.6	625.9	1083.2	457.3	2.37	2.48	4.5						
8	96.3	96.3	96.3	62.7	62.7	62.7	1083.4	629.3	1084.1	454.7	2.38	2.48	3.9						
9	96.2	96.3	96.3	62.9	63.2	63.0	1081.3	626.6	1082.1	455.5	2.37	2.48	4.3						
10	96.3	96.4	96.3	62.5	63.8	63.1	1086.5	631.2	1087.3	456.1	2.38	2.48	3.9						
22	96.2	96.3	96.2	63.8	63.8	63.8	1089.2	629.2	1090.1	460.9	2.36	2.48	4.7						
23	96.1	96.2	96.2	63.0	61.7	62.4	1059.5	610.2	1060.1	449.9	2.35	2.48	5.0						
24	96.3	96.3	96.3	63.7	63.5	63.6	1078.6	617.8	1079.3	461.6	2.34	2.48	5.8						
25	96.4	96.3	96.3	63.0	64.0	63.5	1088.3	631.5	1089.1	457.5	2.38	2.48	4.1						
26	96.3	96.2	96.2	62.8	63.9	63.3	1083.4	627.1	1084.0	456.9	2.37	2.48	4.4						

Field Samples Mix1													
S#	D1	D2	Dav	H1	H2	Hav	WD1	WW	WD2	VOLUME	BULK DENSITY	MAX SG	% A V
	mm	mm	mm	mm	mm	mm	gm	gm	gm	cc	gm/cc	gm/cc	
27	96.2	96.5	96.3	63.7	62.9	63.3	1030.3	583.4	1031.2	447.9	2.30	2.48	7.2
28	96.8	97.7	97.3	63.9	64.4	64.1	1052.7	596.8	1053.4	456.7	2.31	2.48	7.0
29	96.5	96.2	96.3	61.4	61.5	61.5	1018.9	577.9	1019.7	441.8	2.31	2.48	7.0
30	96.4	96.2	96.3	61.2	63.0	62.1	1026.4	583.7	1027.1	443.4	2.31	2.48	6.7
31	95.6	96.1	95.8	63.9	66.0	65.0	1076.5	612.7	1077.2	464.5	2.32	2.48	6.6
32	96.2	96.0	96.1	62.3	63.1	62.7	1042.9	592.9	1043.6	450.6	2.31	2.48	6.7
33	96.4	96.3	96.3	64.0	62.7	63.4	1029.8	584.8	1030.5	445.7	2.31	2.48	6.8
34	96.4	96.3	96.4	63.5	65.5	64.5	1062.2	604.7	1063.1	458.4	2.32	2.48	6.6
35	96.0	96.2	96.1	61.8	63.7	62.7	1035.8	589.4	1036.6	447.2	2.32	2.48	6.6
36	96.1	96.2	96.1	65.2	63.1	64.1	1048.1	592.3	1048.9	456.6	2.30	2.48	7.4
37	96.0	96.3	96.2	63.1	64.0	63.5	1058.3	602.4	1059.1	456.7	2.32	2.48	6.6
38	96.1	96.4	96.3	60.2	62.3	61.2	1015.9	577.2	1016.7	439.5	2.31	2.48	6.8
39	96.2	96.4	96.3	63.7	66.0	64.8	1074.1	610.2	1074.8	464.6	2.31	2.48	6.8
40	96.2	96.2	96.2	61.0	63.9	62.4	1027.9	583.4	1028.5	445.0	2.31	2.48	6.9
41	96.2	96.2	96.2	63.5	63.8	63.7	1057.3	599.3	1058.0	458.7	2.30	2.48	7.1
42	96.3	96.2	96.2	64.4	64.9	64.6	1063.6	601.8	1064.5	462.7	2.30	2.48	7.3
43	96.2	96.2	96.2	64.4	62.9	63.6	1029.8	578.8	1030.6	451.9	2.28	2.48	8.1
44	96.3	96.2	96.3	62.9	64.2	63.5	1051.8	595.9	1052.4	456.5	2.30	2.48	7.1
45	96.2	96.6	96.4	64.1	63.9	64.0	1064.0	604.0	1064.7	460.7	2.31	2.48	6.9
46	96.2	96.7	96.4	63.7	64.0	63.9	1049.5	591.7	1050.3	458.6	2.29	2.48	7.7
47	96.4	96.4	96.4	61.0	63.6	62.3	1008.9	565.2	1009.9	444.7	2.27	2.48	8.5
48	96.2	96.2	96.2	62.8	64.0	63.4	1046.8	590.3	1047.7	457.5	2.29	2.48	7.7
49	96.2	96.4	96.3	64.0	64.0	64.0	1063.3	602.5	1064.1	461.6	2.30	2.48	7.1
50	96.2	96.6	96.4	64.1	64.2	64.1	1068.8	607.4	1069.5	462.1	2.31	2.48	6.7
51	96.3	96.2	96.2	64.1	63.8	63.9	1069.6	606.8	1070.2	463.4	2.31	2.48	6.9

Field Samples Mix1													
S#	D1	D2	Dav	H1	H2	Hav	WD1	WW	WD2	VOLUME	BULK DENSITY	MAX SG	% A V
	mm	mm	mm	mm	mm	mm	gm	gm	gm	cc	gm/cc	gm/cc	
52	96.3	96.5	96.4	64.1	64.4	64.2	1071.4	609.4	1072.0	462.6	2.32	2.48	6.6
53	96.2	96.2	96.2	64.2	63.6	63.9	1061.9	602.9	1062.7	459.8	2.31	2.48	6.9
54	96.3	96.3	96.3	63.9	63.7	63.8	1076.7	617.2	1077.4	460.2	2.34	2.48	5.7
55	96.2	96.3	96.3	64.6	64.1	64.3	1078.2	614.5	1079.1	464.5	2.32	2.48	6.4
56	96.3	96.4	96.3	64.3	64.0	64.1	1071.0	607.9	1071.6	463.7	2.31	2.48	6.9
57	96.0	96.3	96.2	64.0	62.5	63.3	1050.6	598.4	1051.5	453.1	2.32	2.48	6.5
58	96.1	96.2	96.1	64.0	63.3	63.6	1073.8	618.9	1074.6	455.7	2.36	2.48	5.0
59	96.2	96.2	96.2	63.8	63.9	63.8	1078.0	617.8	1078.9	461.1	2.34	2.48	5.7
60	96.1	96.1	96.1	63.5	64.1	63.8	1062.3	604.1	1063.7	459.5	2.31	2.48	6.8
61	96.2	96.6	96.4	64.0	63.8	63.9	1076.3	614.6	1077.0	462.4	2.33	2.48	6.1
62	96.5	96.3	96.4	63.5	63.7	63.6	1078.2	618.2	1079.0	460.7	2.34	2.48	5.6
63	96.4	96.3	96.3	63.1	64.0	63.5	1075.3	618.4	1076.0	457.6	2.35	2.48	5.2
64	66.5	96.4	81.4	64.2	64.5	64.3	1083.1	618.1	1083.6	465.5	2.33	2.48	6.2
65	96.3	96.4	96.3	62.9	64.0	63.4	1012.0	555.8	1013.5	457.7	2.21	2.48	10.8
66	96.3	96.7	96.5	64.3	64.3	64.3	1030.9	569.0	1031.8	462.7	2.23	2.48	10.2
67	96.3	96.3	96.3	63.6	63.7	63.6	1027.7	569.5	1028.6	459.0	2.24	2.48	9.7
68	96.5	96.3	96.4	64.0	64.1	64.0	1045.0	584.6	1045.8	461.2	2.27	2.48	8.6
69	96.4	96.5	96.4	63.7	64.2	63.9	1053.3	593.3	1054.1	460.8	2.29	2.48	7.8
70	96.7	96.7	96.7	63.8	63.4	63.6	1048.6	589.1	1049.3	460.2	2.28	2.48	8.1
71	96.2	96.5	96.4	63.8	63.6	63.7	1052.9	594.1	1053.6	459.5	2.29	2.48	7.6
72	96.3	96.4	96.3	64.2	63.9	64.0	1056.1	596.0	1056.8	460.8	2.29	2.48	7.6
73	96.4	96.5	96.4	63.4	63.9	63.6	1069.4	609.1	1070.1	461.0	2.32	2.48	6.5
74	96.4	97.0	96.7	63.2	64.0	63.6	1055.8	599.5	1056.5	457.0	2.31	2.48	6.8
75	96.3	96.4	96.4	63.8	63.7	63.8	1068.2	608.2	1068.8	460.6	2.32	2.48	6.5

Field Samples Mix2

S#	D1	D2	Dav	H1	H2	Hav	WD1	WW	WD2	VOLUME	BULK DENSITY	MAX SG	% A V
	mm	mm	mm	mm	mm	mm	gm	gm	gm	cc	gm/cc	gm/cc	
3	96.6	96.5	96.5	63.4	63.5	63.5	1018.8	561.0	1019.2	458.2	2.22	2.48	10.4
25	96.2	96.2	96.2	63.5	63.5	63.5	1062.1	607.4	1063.1	455.8	2.33	2.48	6.0
26	96.3	96.4	96.3	63.5	63.0	63.3	1053.8	601.2	1054.9	453.8	2.32	2.48	6.4
4	96.3	96.6	96.5	64.4	64.3	64.3	1036.9	576.1	1037.3	461.2	2.25	2.48	9.3
5	96.5	96.5	96.5	63.8	64.0	63.9	1036.5	576.1	1036.7	460.6	2.25	2.48	9.3
6	96.4	96.5	96.4	63.6	63.9	63.7	1037.2	577.2	1037.5	460.2	2.25	2.48	9.1
7	96.3	96.4	96.4	64.3	64.4	64.3	1035.9	574.0	1036.9	462.9	2.24	2.48	9.8
8	96.2	96.2	96.2	64.4	63.6	64.0	1036.1	576.2	1037.2	461.1	2.25	2.48	9.4
9	96.7	96.6	96.7	63.9	64.1	64.0	1038.3	578.6	1039.4	460.9	2.25	2.48	9.2
10	96.8	96.8	96.8	64.5	64.0	64.3	1046.5	584.2	1047.7	463.4	2.26	2.48	8.9
11	96.6	96.9	96.7	64.0	64.1	64.1	1044.4	584.1	1045.4	461.3	2.26	2.48	8.7
12	96.7	97.2	96.9	62.8	63.3	63.1	1032.4	580.1	1033.3	453.3	2.28	2.48	8.2
13	96.5	96.6	96.5	62.9	63.4	63.2	1044.0	589.6	1045.1	455.5	2.29	2.48	7.6
14	96.4	96.7	96.6	64.0	63.6	63.8	1052.8	593.0	1053.7	460.8	2.28	2.48	7.9
15	96.7	96.7	96.7	64.4	63.7	64.1	1052.4	594.0	1053.1	459.1	2.29	2.48	7.6
16	96.5	96.5	96.5	64.3	64.1	64.2	1069.2	608.2	1070.2	462.0	2.31	2.48	6.7
17	96.5	96.3	96.4	64.2	63.6	63.9	1063.0	605.3	1063.8	458.5	2.32	2.48	6.5
18	96.3	96.5	96.4	64.3	63.4	63.9	1053.8	598.1	1054.9	456.8	2.31	2.48	7.0
19	96.5	96.5	96.5	63.5	64.1	63.8	1055.9	595.1	1056.8	461.7	2.29	2.48	7.8
20	96.6	96.4	96.5	63.9	63.5	63.7	1046.6	590.6	1047.7	457.2	2.29	2.48	7.7
21	96.4	96.5	96.4	62.3	63.9	63.1	1062.3	604.0	1063.0	459.0	2.31	2.48	6.7
22	96.3	96.3	96.3	64.3	63.6	64.0	1046.8	594.9	1047.6	452.7	2.31	2.48	6.8
23	96.1	96.2	96.1	63.2	64.0	63.6	1057.7	599.3	1059.3	459.9	2.30	2.48	7.3
24	96.2	96.2	96.2	63.2	63.8	63.5	1045.9	590.0	1046.9	456.9	2.29	2.48	7.7
1	96.4	96.4	96.4	63.8	62.8	63.3	1018.8	562.8	1019.3	456.5	2.23	2.48	10.0
2	96.1	96.4	96.3	64.5	63.5	64.0	1023.0	560.2	1023.5	463.3	2.21	2.48	11.0

Field Samples Mix2													
S#	D1	D2	Dav	H1	H2	Hav	WD1	WW	WD2	VOLUME	BULK DENSITY	MAX SG	% A V
	mm	mm	mm	mm	mm	mm	gm	gm	gm	cc	gm/cc	gm/cc	
27	96.1	96.3	96.2	63.4	63.4	63.4	1082.8	624.4	1083.3	458.8	2.36	2.48	4.8
28	96.4	96.5	96.4	63.7	63.2	63.5	1076.0	618.3	1076.5	458.3	2.35	2.48	5.3
29	96.5	96.4	96.4	63.8	63.8	63.8	1101.4	640.4	1102.1	461.7	2.39	2.48	3.8
30	96.2	96.4	96.3	63.6	64.0	63.8	1095.6	634.9	1096.1	461.3	2.38	2.48	4.2
31	96.3	96.3	96.3	64.0	64.4	64.2	1097.9	634.5	1098.5	464.0	2.37	2.48	4.6
32	96.4	96.3	96.3	64.0	63.6	63.8	1093.0	631.6	1093.6	462.1	2.37	2.48	4.6
33	96.4	96.4	96.4	63.8	64.3	64.1	1085.3	623.4	1086.1	462.7	2.35	2.48	5.4
34	96.4	96.4	96.4	63.8	63.8	63.8	1079.7	618.7	1080.5	461.8	2.34	2.48	5.7
35	96.3	96.4	96.3	63.5	63.9	63.7	1074.7	614.2	1075.4	461.2	2.33	2.48	6.0
36	96.2	96.4	96.3	63.3	63.8	63.6	1073.8	614.3	1074.6	460.3	2.33	2.48	5.9
37	96.8	96.4	96.6	63.7	63.9	63.8	1079.7	617.9	1080.6	462.7	2.33	2.48	5.9
38	96.4	96.3	96.3	63.4	63.8	63.6	1073.6	613.9	1074.5	460.6	2.33	2.48	6.0
39	96.4	96.3	96.3	63.8	63.7	63.7	1075.3	614.5	1075.9	461.4	2.33	2.48	6.0
40	96.4	96.3	96.3	63.8	63.6	63.7	1076.7	617.1	1077.5	460.4	2.34	2.48	5.7
41	96.5	96.4	96.4	64.1	64.0	64.0	1078.3	615.8	1079.1	463.4	2.33	2.48	6.2
42	96.4	96.5	96.4	63.8	64.0	63.9	1067.8	609.8	1068.4	458.6	2.33	2.48	6.1
43	96.3	96.5	96.4	63.5	63.6	63.5	1073.2	613.2	1074.5	461.3	2.33	2.48	6.2
44	96.4	96.4	96.4	64.1	64.0	64.1	1079.7	617.6	1080.5	462.9	2.33	2.48	6.0
45	96.4	96.5	96.4	63.9	63.8	63.9	1056.0	593.7	1056.7	463.1	2.28	2.48	8.0
46	96.3	96.5	96.4	63.6	64.1	63.8	1056.3	594.7	1057.0	462.3	2.28	2.48	7.9
47	96.5	96.6	96.6	63.8	64.0	63.9	1049.4	587.4	1050.0	462.6	2.27	2.48	8.5
48	96.5	96.6	96.6	63.7	63.9	63.8	1045.9	583.5	1046.9	463.4	2.26	2.48	9.0
49	96.8	96.5	96.6	63.8	64.5	64.1	1096.8	633.3	1097.5	464.2	2.36	2.48	4.7
50	96.5	96.6	96.5	63.7	63.8	63.8	1096.2	634.2	1097.0	462.8	2.37	2.48	4.5
51	96.7	96.5	96.6	63.8	63.0	63.4	1104.9	643.9	1105.6	461.6	2.39	2.48	3.5

Field Samples Mix2

S#	D1	D2	Dav	H1	H2	Hav	WD1	WW	WD2	VOLUME	BULK DENSITY	MAX SG	% A V
	mm	mm	mm	mm	mm	mm	gm	gm	gm	cc	gm/cc	gm/cc	
52	96.4	96.6	96.5	63.7	63.7	63.7	1111.9	649.8	1112.5	462.7	2.40	2.48	3.1
53	96.4	96.6	96.5	63.8	63.7	63.7	1089.4	628.6	1090.2	461.5	2.36	2.48	4.8
54	96.5	96.7	96.6	64.3	63.1	63.7	1095.5	635.4	1096.3	460.9	2.38	2.48	4.2
55	96.5	96.6	96.5	63.6	63.6	63.6	1101.2	639.2	1102.0	462.8	2.38	2.48	4.0
56	96.9	96.8	96.9	63.9	63.4	63.7	1107.8	645.2	1108.4	463.2	2.39	2.48	3.6
57	96.5	96.6	96.5	63.8	63.3	63.5	1089.9	630.6	1090.7	460.1	2.37	2.48	4.5
58	96.6	96.5	96.5	64.0	63.9	63.9	1101.1	637.3	1102.0	464.6	2.37	2.48	4.4
59	96.6	96.5	96.6	63.8	63.7	63.7	1103.4	641.5	1104.2	462.7	2.38	2.48	3.8
60	96.5	96.4	96.5	63.6	63.4	63.5	1107.2	645.1	1107.8	462.8	2.39	2.48	3.5
61	96.6	96.7	96.7	63.9	63.4	63.6	1099.5	637.0	1100.3	463.2	2.37	2.48	4.3
62	96.6	96.6	96.6	63.7	63.6	63.6	1099.5	638.0	1100.1	462.1	2.38	2.48	4.1
63	96.9	96.4	96.6	63.5	63.2	63.4	1099.7	639.7	1100.4	460.8	2.39	2.48	3.8
64	96.5	96.6	96.5	63.6	63.9	63.8	1111.9	648.5	1112.5	464.0	2.40	2.48	3.4
65	96.6	96.6	96.6	63.8	63.9	63.8	1091.3	628.2	1092.1	463.9	2.35	2.48	5.1
66	96.9	96.8	96.8	63.1	63.6	63.4	1104.8	641.0	1105.5	464.5	2.38	2.48	4.1
67	97.0	96.9	97.0	63.6	63.7	63.7	1109.8	645.7	1110.7	465.0	2.39	2.48	3.8
68	97.1	97.2	97.1	63.1	63.2	63.1	1090.8	626.3	1091.7	465.4	2.34	2.48	5.5
69	97.0	96.9	96.9	63.5	63.5	63.5	1106.4	640.1	1107.4	467.4	2.37	2.48	4.5
70	96.9	96.9	96.9	63.5	63.5	63.5	1108.4	643.1	1109.3	466.2	2.38	2.48	4.1
71	96.8	96.9	96.8	63.8	63.8	63.8	1071.4	607.2	1072.2	465.0	2.30	2.48	7.1
72	96.7	97.1	96.9	63.6	63.8	63.7	1082.2	617.8	1082.9	465.0	2.33	2.48	6.2

Field Samples Mix2														
S#	D1	D2	Dav	H1	H2	Hav	WD1	WW	WD2	VOLUME	BULK DENSITY	MAX SG	% A V	
	mm	mm	mm	mm	mm	mm	gm	gm	gm	cc	gm/cc	gm/cc		
73	97.0	97.1	97.0	63.8	63.9	0.0	1088.5	624.9	1089.2	464.3	2.34	2.48	5.5	
74	97.1	97.0	97.0	63.6	63.6	63.6	1069.1	605.0	1069.9	464.9	2.30	2.48	7.3	
75	96.9	96.9	96.9	63.7	63.9	63.8	1082.2	616.3	1082.9	466.6	2.32	2.48	6.5	
76	97.0	96.9	96.9	63.8	63.7	63.8	1088.3	623.8	1089.1	465.3	2.34	2.48	5.7	
77	97.1	97.2	97.1	63.4	65.5	64.5	1098.6	628.5	1099.4	470.9	2.33	2.48	5.9	
78	97.8	97.5	97.6	63.3	63.4	63.3	1084.1	618.0	1084.8	466.9	2.32	2.48	6.4	
79	97.4	97.7	97.6	62.6	62.3	62.4	1060.4	602.7	1061.3	458.6	2.31	2.48	6.8	
80	97.3	97.4	97.4	63.4	62.9	63.2	1074.2	611.7	1075.1	463.4	2.32	2.48	6.5	
81	97.4	97.6	97.5	62.3	62.8	62.5	1080.6	621.5	1081.2	459.7	2.35	2.48	5.2	
82	97.5	97.5	97.5	63.6	63.0	63.3	1099.4	632.7	1100.0	467.2	2.35	2.48	5.1	
83	97.5	97.3	97.4	63.9	63.8	63.8	1097.7	630.0	1098.3	468.3	2.34	2.48	5.5	
84	97.5	97.5	97.5	63.5	63.4	63.5	1089.5	622.4	1090.5	468.1	2.33	2.48	6.2	
85	97.3	97.5	97.4	65.4	63.7	64.6	1117.7	645.5	1118.4	472.8	2.36	2.48	4.7	
86	97.5	97.5	97.5	62.5	63.5	63.0	1094.0	631.2	1094.5	463.3	2.36	2.48	4.8	
87	97.9	97.8	97.8	62.6	65.0	63.8	1101.7	633.9	1102.5	468.6	2.35	2.48	5.2	
88	97.3	97.4	97.3	63.4	64.7	64.0	1106.1	636.9	1106.9	470.0	2.35	2.48	5.1	
89	98.2	98.0	98.1	63.3	63.1	63.2	1104.4	639.1	1105.3	466.2	2.37	2.48	4.5	
90	97.3	97.4	97.4	63.1	63.3	63.2	1101.8	636.7	1102.6	465.9	2.36	2.48	4.7	
91	97.4	97.5	97.4	63.4	64.4	63.9	1118.6	644.6	1119.3	474.8	2.36	2.48	5.0	
92	97.9	97.4	97.6	63.3	65.2	64.2	1114.5	643.1	1115.2	472.1	2.36	2.48	4.8	
93	97.6	98.0	97.8	60.7	63.4	62.0	1068.2	619.7	1069.0	449.3	2.38	2.48	4.1	
94	97.4	98.0	97.7	61.1	63.0	62.1	1075.1	621.9	1075.8	453.9	2.37	2.48	4.5	
95	97.4	97.4	97.4	60.5	63.3	61.9	1070.9	616.5	1071.9	455.4	2.35	2.48	5.2	

APPENDIX 3

MOISTURE INDUCED DAMAGE ANALYSIS						MIX TYPE		Mix3	
TENSILE STRENGTH RATIO						TEST METHOD		PWGSC	
SAMPLE		CONDITIONED				UNCONDITIONED			
		504	505	506	507	501	502	503	508
DRY MASS, g	A	1046.4	1244.3	1164.8	1198.2	1178	1114.4	1153.8	1264
SSD MASS, g	B	1047.1	1244.5	1165.5	1198.5	1178.7	1114.8	1154.3	1264.5
MASS IN WATER, g	C	617.7	733	681.8	704.2	695.9	658.3	675.6	736.9
VOLUME, CC (B-C)	E	429.4	511.5	483.7	494.3	482.8	456.5	478.7	527.6
BULK SG (A/E)	F	2.44	2.43	2.41	2.42	2.44	2.44	2.41	2.40
AVERAGE BULK SG		2.43				2.42			
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	1.74	1.91	2.90	2.26	1.62	1.57	2.81	3.40
AVERAGE AIR VOIDS		2.20				2.35			
STABILITY		2526.9	3193.63	2632.01	2694.09	3351.23	2981.29	2479.76	3381.78
CORRECTION FACTOR		1.39	1.00	1.09	1.09	1.09	1.19	1.14	0.96
CORRECTD STABILITY		3512.4	3193.6	2868.9	2936.6	3652.8	3547.7	2826.9	3246.5
AVERAGE STABILITY		3127.9				3318.5			
RETAINED STABILITY		94.3							
REMARKS:									

MOISTURE INDUCED DAMAGE ANALYSIS					MIX TYPE		Mix2
TENSILE STRENGTH RATIO					TEST METHOD		MTO
		CONDITIONED			UNCONDITIONED		
SAMPLE		51	52	54	53	55	56
DRY MASS, g	A	1238.2	1230.8	1261.4	1299.8	1119.2	1162.3
SSD MASS, g	B	1241.6	1235	1265.2	1302.5	1121.2	1164.2
MASS IN WATER, g	C	687.9	684.1	698.5	724.1	619.8	651.9
VOLUME,CC (B-C)	E	553.7	550.9	566.7	578.4	501.4	512.3
BULK SG (A/E)	F	2.24	2.23	2.23	2.25	2.23	2.27
AVERAGE BULK SG		2.23			2.25		
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	9.83	9.91	10.25	9.39	9.99	8.52
AVERAGE AIR VOIDS		10.00			9.30		
STABILITY		4191.16	4206.88	4537.48	6115.23	4936.41	5665.99
CORRECTION FACTOR		0.89	0.89	0.86	0.83	1.04	1.00
CORRECTD STABILITY		3730.13	3744.12	3902.23	5075.64	5133.87	5665.99
AVERAGE STABILITY		3792.2			5291.8		
RETAINED STABILITY		71.7					

MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		Mix3	
TENSILE STRENGTH RATIO				TEST METHOD		MTO	
		CONDITIONED			UNCONDITIONED		
SAMPLE		54	55	56	51	52	53
DRY MASS, g	A	1054	1081.6	1036.8	1141.9	1061.6	1065
SSD MASS, g	B	1062.1	1089.2	1044.3	1153.9	1069.6	1073.6
MASS IN WATER, g	C	587.2	599.5	577.1	637.7	590.1	593
VOLUME,CC (B-C)	E	474.9	489.7	467.2	516.2	479.5	480.6
BULK SG (A/E)	F	2.22	2.21	2.22	2.21	2.21	2.22
AVERAGE BULK SG		2.22			2.21		
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	10.51	10.94	10.52	10.80	10.73	10.65
AVERAGE AIR VOIDS		10.65			10.72		
STABILITY		3222.18	3518.73	3089.21	4458.09	3461.56	4264.23
CORRECTION FACTOR		1.14	1.09	1.19	1.00	1.14	1.14
CORRECTD STABILITY		3673.29	3835.42	3676.16	4458.09	3946.18	4861.22
AVERAGE STABILITY		3728.3			4421.8		
RETAINED STABILITY		84.3					
REMARKS:							

MOISTURE INDUCED DAMAGE ANALYSIS						MIX TYPE		Mix1
TENSILE STRENGTH RATIO						TEST METHOD		MTO
				CONDITIONED			UNCONDITIONED	
SAMPLE			3	5	6	1	2	4
DRY MASS, g	A		1090.67	1101	1087.02	1105.04	1098.08	1090.91
SSD MASS, g	B		1090.95	1101.47	1087.47	1105.47	1098.44	1091.27
MASS IN WATER, g	C		629.67	638.15	628.59	641.29	633.96	632.16
VOLUME, CC (B-C)	E		461.28	463.32	458.88	464.18	464.48	459.11
BULK SG (A/E)	F		2.36	2.38	2.37	2.38	2.36	2.38
AVERAGE BULK SG			2.37			2.37		
MAX SG	G		2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H		4.66	4.18	4.48	4.01	4.67	4.19
AVERAGE AIR VOIDS			4.44			4.29		
STABILITY			2611.32	3031.51	2871.86	4554.7	4434.53	4219.72
CORRECTION FACTOR			1.19	1.19	1.19	1.19	1.19	1.19
CORRECTD STABILITY			3107.47	3607.50	3417.51	5420.09	5277.09	5021.47
AVERAGE STABILITY			3377.5			5239.6		
RETAINED STABILITY			64.5					
REMARKS:								

MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		SM1	
TENSILE STRENGTH RATIO				TEST METHOD		ASTM D4867	
SAMPLE		83	84	86	81	82	85
DIAMETER, mm	D	101.50	105.50	101.50	101.40	101.40	101.30
THICKNESS, mm	t	61.10	63.40	57.70	61.40	60.10	67.70
DRY MASS, g	A	1105.00	1141.80	1041.10	1105.70	1092.70	1233.40
SSD MASS, g	B	1107.10	1143.80	1042.30	1107.90	1094.10	1235.50
MASS IN WATER, g	C	621.30	641.00	584.10	625.20	618.00	696.20
VOLUME,CC (B-C)	E	485.80	502.80	458.20	482.70	476.10	539.30
BULK SG (A/E)	F	2.27	2.27	2.27	2.29	2.30	2.29
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	8.28	8.43	8.38	7.63	7.46	7.78
VOL AIR VOIDS (HE/100)	I	40.24	42.40	38.40	36.85	35.50	41.96
AVERAGE AIR VOIDS		8			8		
SATURATED							
SSD MASS, g	B'	1135.60	1172.90	1069.50			
MASS IN WATER, g	C'	649.60	669.85	610.83			
VOLUME,CC (B-C)	E'	486.00	503.05	458.67			
VOL ABS WATER, CC (B'-A)	J'	30.60	31.10	28.40			
% SATURATION (100J'/I)		76.05	73.35	73.96			
% SWELL (100(E'-E)/E)		0.04	0.05	0.10			
AVERAGE SATURATION		74.45					
AVERAGE SWELL		0.06					
CONDITIONED							
THICKNESS, mm	t''	61.10	63.10	57.70			
SSD MASS, g	B''	1138.80	1176.80	1074.20			
MASS IN WATER, g	C''	651.10	671.60	613.80			
VOLUME,CC (B''-C'')	E''	487.70	505.20	460.40			
VOL ABS WATER, CC (B'-A)	J''	33.80	35.00	33.10			
% SATURATION (100J'/I)		84.01	82.55	86.19			
% SWELL (100(E'-E)/E)		0.39	0.48	0.48			
AVERAGE SATURATION		84.25					
AVERAGE SWELL		0.45					
TENSILE STRENGTH							
LOAD, N	P	1251.20	1250.70	1118.72	1624.60	1593.58	1777.18
DRY STR (2000P/(T*D*3.14) Std					0.17	0.17	0.17
WET STR (2000P/(T*D*3.14) Stm		0.13	0.12	0.12			
AVG DRY STR (kpa):	0.166	AVG WET STR (kpa):		0.123	TSR, %	74.3	
REMARKS:							

MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		BASE	
TENSILE STRENGTH RATIO				TEST METHOD		ASTM D4867	
SAMPLE		112	113	114	111	115	116
DIAMETER, mm	D	101.30	101.70	101.50	101.50	101.50	101.40
THICKNESS, mm	t	64.40	57.70	61.70	61.30	61.50	62.60
DRY MASS, g	A	1124.10	1029.40	1099.50	1116.10	1089.00	1072.50
SSD MASS, g	B	1132.50	1034.60	1106.30	1121.90	1093.80	1083.10
MASS IN WATER, g	C	640.80	584.50	626.10	641.70	619.80	608.70
VOLUME,CC (B-C)	E	491.70	450.10	480.20	480.20	474.00	474.40
BULK SG (A/E)	F	2.29	2.29	2.29	2.32	2.30	2.26
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	7.82	7.78	7.67	6.43	7.36	8.84
VOL AIR VOIDS (HE/100)	I	38.43	35.02	36.85	30.88	34.89	41.94
AVERAGE AIR VOIDS		8			8		
SATURATED							
SSD MASS, g	B'	1154.20	1057.10	1128.10			
MASS IN WATER, g	C'	662.10	606.60	647.60			
VOLUME,CC (B-C)	E'	492.10	450.50	480.50			
VOL ABS WATER, CC (B'-A) J'		30.10	27.70	28.60			
% SATURATION (100J'/I)		78.32	79.10	77.61			
% SWELL (100(E'-E)/E)		0.08	0.09	0.06			
AVERAGE SATURATION		78.34					
AVERAGE SWELL		0.08					
CONDITIONED							
THICKNESS, mm	t''	64.40	57.70	61.70			
SSD MASS, g	B''	1157.10	1060.20	1131.20			
MASS IN WATER, g	C''	662.80	607.60	648.70			
VOLUME,CC (B''-C'')	E''	494.30	452.60	482.50			
VOL ABS WATER, CC (B'-A) J''		33.00	30.80	31.70			
% SATURATION (100J'/I)		85.86	87.95	86.02			
% SWELL (100(E'-E)/E)		0.53	0.56	0.48			
AVERAGE SATURATION		86.61					
AVERAGE SWELL		0.52					
TENSILE STRENGTH							
LOAD, N	P	1302.90	1378.33	1339.39	2256.17	1922.16	1448.23
DRY STR (2000P/(T*D*3.14) Std					0.23	0.20	0.15
WET STR (2000P/(T*D*3.14) Str		0.13	0.15	0.14			
AVG DRY STR (kpa):		0.191	AVG WET STR (kpa):		0.138	TSR, %	72.2
REMARKS:							

MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		SM2	
TENSILE STRENGTH RATIO				TEST METHOD		ASTM D4867	
SAMPLE		112	116	117	111	114	115
DIAMETER, mm	D	101.50	101.60	101.70	101.50	101.40	101.50
THICKNESS, mm	t	58.5	68.3	63.5	66.5	64.5	72.1
DRY MASS, g	A	1081.30	1260.30	1171.30	1233.20	1178.50	1323.30
SSD MASS, g	B	1082.60	1262.40	1174.00	1234.70	1180.10	1326.30
MASS IN WATER, g	C	614.00	714.50	664.70	702.30	663.50	752.20
VOLUME,CC (B-C)	E	468.60	547.90	509.30	532.40	516.60	574.10
BULK SG (A/E)	F	2.31	2.30	2.30	2.32	2.28	2.30
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	6.96	7.25	7.27	6.60	8.01	7.06
VOL AIR VOIDS (HE/100)	I	32.59	39.71	37.00	35.14	41.40	40.51
AVERAGE AIR VOIDS		7			7		
SATURATED							
SSD MASS, g	B'	1104.90	1289.90	1198.40			
MASS IN WATER, g	C'	636.20	741.60	689.00			
VOLUME,CC (B-C)	E'	468.70	548.30	509.40			
VOL ABS WATER, CC (B'-A) J'		23.60	29.60	27.10			
% SATURATION (100J'/I)		72.41	74.53	73.24			
% SWELL (100(E'-E)/E)		0.02	0.07	0.02			
AVERAGE SATURATION		73.39					
AVERAGE SWELL		0.04					
CONDITIONED							
THICKNESS, mm	t''	58.53	68.33	63.50			
SSD MASS, g	B''	1107.90	1292.50	1202.80			
MASS IN WATER, g	C''	637.40	742.20	691.40			
VOLUME,CC (B''-C'')	E''	470.50	550.30	511.40			
VOL ABS WATER, CC (B'-A) J''		26.60	32.20	31.50			
% SATURATION (100J''/I)		81.62	81.08	85.13			
% SWELL (100(E''-E)/E)		0.41	0.44	0.41			
AVERAGE SATURATION		82.61					
AVERAGE SWELL		0.42					
TENSILE STRENGTH							
LOAD, N	P	899.45	1086.64	1104.39	1176.79	1751.72	1751.72
DRY STR (2000P/(T*D*3.14) Std					0.11	0.17	0.15
WET STR (2000P/(T*D*3.14) Str		0.10	0.10	0.11			
AVG DRY STR (kpa):		0.145	AVG WET STR (kpa):		0.102	TSR, %	70.3
REMARKS:							

MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		SM1	
TENSILE STRENGTH RATIO				TEST METHOD		AASHTO	
SAMPLE		87	88	89	810	811	812
DIAMETER, mm	D	101.30	101.50	101.60	101.40	101.50	101.30
THICKNESS, mm	t	69.00	66.90	66.90	66.60	63.80	65.80
DRY MASS, g	A	1255.60	1206.40	1202.20	1215.40	1149.80	1188.60
SSD MASS, g	B	1258.90	1209.30	1212.90	1217.00	1152.40	1190.20
MASS IN WATER, g	C	712.30	678.10	683.40	685.90	646.70	671.00
VOLUME,CC (B-C)	E	546.60	531.20	529.50	531.10	505.70	519.20
BULK SG (A/E)	F	2.30	2.27	2.27	2.29	2.27	2.29
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	7.37	8.42	8.45	7.72	8.32	7.69
VOL AIR VOIDS (HE/100)	I	40.31	44.75	44.74	41.02	42.07	39.93
AVERAGE AIR VOIDS		8			8		
SATURATED							
SSD MASS, g	B'	1285.32	1242.00	1237.20			
MASS IN WATER, g	C'	738.65	710.50	707.50			
VOLUME,CC (B-C)	E'	546.67	531.50	529.70			
VOL ABS WATER, CC (B'-A) J'	J'	29.72	35.60	35.00			
% SATURATION (100J'/I)		73.73	79.56	78.23			
% SWELL (100(E'-E)/E)		0.01	0.06	0.04			
AVERAGE SATURATION		77.17					
AVERAGE SWELL		0.04					
CONDITIONED							
THICKNESS, mm	t''	69.00	66.90	66.90			
SSD MASS, g	B''	1289.85	1246.50	1241.90			
MASS IN WATER, g	C''	740.80	712.30	709.80			
VOLUME,CC (B''-C'')	E''	549.05	534.20	532.10			
VOL ABS WATER, CC (B'-A) J''	J''	34.25	40.10	39.70			
% SATURATION (100J''/I)		84.97	89.61	88.73			
% SWELL (100(E'-E)/E)		0.45	0.56	0.49			
AVERAGE SATURATION		87.77					
AVERAGE SWELL		0.50					
TENSILE STRENGTH							
LOAD, N	P	1296.48	1224.11	1321.63	1670.00	1454.16	1539.00
DRY STR (2000P/(T*D*3.14) Std					0.16	0.14	0.15
WET STR (2000P/(T*D*3.14) Str		0.12	0.11	0.12			
AVG DRY STR (kpa):	0.149	AVG WET STR (kpa):		0.119	TSR, %	79.7	
REMARKS:							

MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		BASE	
TENSILE STRENGTH RATIO				TEST METHOD		AASHTO	
SAMPLE		117	119	1111	118	1110	1112
DIAMETER, mm	D	101.40	101.60	101.60	101.30	101.60	101.50
THICKNESS, mm	t	64.00	66.00	63.10	67.20	54.60	53.20
DRY MASS, g	A	1152.90	1189.10	1133.90	1164.40	963.30	952.10
SSD MASS, g	B	1157.70	1195.10	1138.60	1173.60	967.80	955.70
MASS IN WATER, g	C	659.60	680.60	645.90	666.40	548.00	541.50
VOLUME, CC (B-C)	E	498.10	514.50	492.70	507.20	419.80	414.20
BULK SG (A/E)	F	2.31	2.31	2.30	2.30	2.29	2.30
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	6.67	6.81	7.20	7.43	7.47	7.31
VOL AIR VOIDS (HE/100)	I	33.22	35.02	35.48	37.68	31.37	30.29
AVERAGE AIR VOIDS		7			7		
SATURATED							
SSD MASS, g	B'	1178.70	1215.54	1158.83			
MASS IN WATER, g	C'	680.10	700.50	665.80			
VOLUME, CC (B-C)	E'	498.60	515.04	493.03			
VOL ABS WATER, CC (B'-A) J'		25.80	26.44	24.93			
% SATURATION (100J'/I)		77.66	75.49	70.26			
% SWELL (100(E'-E)/E)		0.10	0.10	0.07			
AVERAGE SATURATION		74.47					
AVERAGE SWELL		0.09					
CONDITIONED							
THICKNESS, mm	t''	64.00	66.00	63.10			
SSD MASS, g	B''	1181.60	1219.80	1162.50			
MASS IN WATER, g	C''	680.50	701.80	667.10			
VOLUME, CC (B''-C'')	E''	501.10	518.00	495.40			
VOL ABS WATER, CC (B'-A) J''		28.70	30.70	28.60			
% SATURATION (100J''/I)		86.39	87.65	80.60			
% SWELL (100(E''-E)/E)		0.60	0.68	0.55			
AVERAGE SATURATION		84.88					
AVERAGE SWELL		0.61					
TENSILE STRENGTH							
LOAD, N	P	1600.00	1248.23	1261.58	1387.64	1676.30	1734.93
DRY STR (2000P/(T*D*3.14) Std					0.13	0.19	0.20
WET STR (2000P/(T*D*3.14) Str		0.16	0.12	0.13			
AVG DRY STR (kpa):		0.176	AVG WET STR (kpa):		0.134	TSR, %	76.1
REMARKS:							

MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		SM2	
TENSILE STRENGTH RATIO				TEST METHOD		AASHTO	
SAMPLE		118	1110	1111	113	119	1112
DIAMETER, mm	D	101.50	101.60	101.40	101.50	101.50	101.50
THICKNESS, mm	t	59.5	60.0	67.4	67.1	58.3	63.8
DRY MASS, g	A	1087.90	1260.30	1084.50	1250.10	1056.70	1163.10
SSD MASS, g	B	1090.20	1262.40	1086.30	1251.60	1059.40	1165.00
MASS IN WATER, g	C	618.20	714.50	614.30	714.70	597.50	655.80
VOLUME,CC (B-C)	E	472.00	547.90	472.00	536.90	461.90	509.20
BULK SG (A/E)	F	2.30	2.30	2.30	2.33	2.29	2.28
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	7.06	7.25	7.35	6.11	7.75	7.90
VOL AIR VOIDS (HE/100)	I	33.33	39.71	34.70	32.83	35.81	40.21
AVERAGE AIR VOIDS		7			7		
SATURATED							
SSD MASS, g	B'	1110.73	1291.30	1110.10			
MASS IN WATER, g	C'	638.54	743.00	637.80			
VOLUME,CC (B-C)	E'	472.19	548.30	472.30			
VOL ABS WATER, CC (B'-A) J'		22.83	31.00	25.60			
% SATURATION (100J'/I)		68.50	78.06	73.77			
% SWELL (100(E'-E)/E)		0.04	0.07	0.06			
AVERAGE SATURATION		73.44					
AVERAGE SWELL		0.06					
CONDITIONED							
THICKNESS, mm	t''	59.45	60.00	67.43			
SSD MASS, g	B''	1114.20	1294.40	1114.10			
MASS IN WATER, g	C''	639.90	743.60	639.70			
VOLUME,CC (B''-C'')	E''	474.30	550.80	474.40			
VOL ABS WATER, CC (B'-A) J''		26.30	34.10	29.60			
% SATURATION (100J'/I)		78.91	85.86	85.30			
% SWELL (100(E'-E)/E)		0.49	0.53	0.51			
AVERAGE SATURATION		83.36					
AVERAGE SWELL		0.51					
TENSILE STRENGTH							
LOAD, N	P	951.17	1080.77	1403.94	1386.16	1463.96	2010.77
DRY STR (2000P/(T*D*3.14) Std					0.13	0.16	0.20
WET STR (2000P/(T*D*3.14) Str		0.10	0.11	0.13			
AVG DRY STR (kpa):	0.162	AVG WET STR (kpa):		0.115	TSR, %	71.0	
REMARKS:							

MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		SM1	
TENSILE STRENGTH RATIO				TEST METHOD		ASTM D4867	
SAMPLE		12	19	21	16	17	20
DIAMETER, mm	D	96.50	96.30	96.20	96.20	63.30	96.20
THICKNESS, mm	t	63.20	63.60	64.10	63.70	63.20	63.40
DRY MASS, g	A	1084.40	1085.20	1092.60	1085.30	1084.60	1066.10
SSD MASS, g	B	1085.40	1086.00	1093.30	1086.10	1085.40	1067.00
MASS IN WATER, g	C	630.40	625.30	630.30	627.40	629.80	609.70
VOLUME,CC (B-C)	E	455.00	460.70	463.00	458.70	455.60	457.30
BULK SG (A/E)	F	2.38	2.36	2.36	2.37	2.38	2.33
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	3.90	5.02	4.85	4.60	4.01	6.00
VOL AIR VOIDS (HE/100)	I	17.74	23.12	22.44	21.08	18.26	27.42
AVERAGE AIR VOIDS		5			5		
SATURATED							
SSD MASS, g	B'	1096.90	1102.20	1108.90			
MASS IN WATER, g	C'	641.76	641.42	645.88			
VOLUME,CC (B-C)	E'	455.14	460.78	463.02			
VOL ABS WATER, CC (B'-A) J'	J'	12.50	17.00	16.30			
% SATURATION (100J'/I)		70.45	73.53	72.65			
% SWELL (100(E'-E)/E)		0.03	0.02	0.00			
AVERAGE SATURATION		72.21					
AVERAGE SWELL		0.02					
CONDITIONED							
THICKNESS, mm	t''	63.20	63.60	64.10			
SSD MASS, g	B''	1100.10	1105.90	1111.80			
MASS IN WATER, g	C''	643.90	643.10	647.10			
VOLUME,CC (B''-C'')	E''	456.20	462.80	464.70			
VOL ABS WATER, CC (B'-A) J''	J''	15.70	20.70	19.20			
% SATURATION (100J''/I)		88.49	89.54	85.58			
% SWELL (100(E''-E)/E)		0.26	0.46	0.37			
AVERAGE SATURATION		87.87					
AVERAGE SWELL		0.36					
TENSILE STRENGTH							
LOAD, N	P	1057.13	915.76	980.81	1085.21	1010.28	1069.39
DRY STR (2000P/(T*D*3.14) Std					0.11	0.16	0.11
WET STR (2000P/(T*D*3.14) Stm		0.11	0.10	0.10			
AVG DRY STR (kpa):		0.128	AVG WET STR (kpa):		0.102	TSR, %	79.7
REMARKS:							

MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		SM2	
TENSILE STRENGTH RATIO				TEST METHOD		ASTM D4867	
SAMPLE		8	14	18	9	12	16
DIAMETER, mm	D	96.20	96.60	96.40	96.70	96.90	96.50
THICKNESS, mm	t	64.00	63.80	63.90	64.00	63.10	64.20
DRY MASS, g	A	1036.10	1052.80	1053.80	1038.30	1032.40	1069.20
SSD MASS, g	B	1037.20	1053.70	1054.90	1039.40	1033.30	1070.20
MASS IN WATER, g	C	576.20	593.00	598.10	578.60	580.10	608.20
VOLUME,CC (B-C)	E	461.00	460.70	456.80	460.80	453.20	462.00
BULK SG (A/E)	F	2.25	2.29	2.31	2.25	2.28	2.31
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	9.37	7.85	6.98	9.14	8.14	6.68
VOL AIR VOIDS (HE/100)	I	43.22	36.18	31.88	42.13	36.91	30.87
AVERAGE AIR VOIDS		8			8		
SATURATED							
SSD MASS, g	B'	1070.40	1081.40	1076.10			
MASS IN WATER, g	C'	609.17	620.32	619.11			
VOLUME,CC (B-C)	E'	461.23	461.08	456.99			
VOL ABS WATER, CC (B'-A)	J'	34.30	28.60	22.30			
% SATURATION (100J'/I)		79.37	79.04	69.95			
% SWELL (100(E'-E)/E)		0.05	0.08	0.04			
AVERAGE SATURATION		76.12					
AVERAGE SWELL		0.06					
CONDITIONED							
THICKNESS, mm	t''	64.00	63.80	63.90			
SSD MASS, g	B''	1074.60	1085.80	1080.50			
MASS IN WATER, g	C''	611.50	622.93	621.10			
VOLUME,CC (B''-C'')	E''	463.10	462.87	459.40			
VOL ABS WATER, CC (B'-A)	J''	38.50	33.00	26.70			
% SATURATION (100J''/I)		89.08	91.20	83.75			
% SWELL (100(E'-E)/E)		0.46	0.47	0.57			
AVERAGE SATURATION		88.01					
AVERAGE SWELL		0.50					
TENSILE STRENGTH							
LOAD, N	P	467.52	535.44	686.18	753.18	828.56	1071.30
DRY STR (2000P/(T*D*3.14) Std					0.08	0.09	0.11
WET STR (2000P/(T*D*3.14) Stm		0.05	0.06	0.07			
AVG DRY STR (kpa):		0.091	AVG WET STR (kpa):		0.058	TSR, %	63.8
REMARKS:							

MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		SMI	
TENSILE STRENGTH RATIO				TEST METHOD		AASHTO	
SAMPLE		11	13	15	7	14	18
DIAMETER, mm	D	96.30	96.20	96.20	96.30	96.20	101.60
THICKNESS, mm	t	62.90	63.70	63.00	63.90	63.80	66.90
DRY MASS, g	A	1087.40	1075.50	1074.40	1090.30	1085.30	1202.20
SSD MASS, g	B	1088.20	1076.50	1075.20	1091.20	1085.90	1212.90
MASS IN WATER, g	C	631.80	617.60	620.50	631.20	625.40	683.40
VOLUME, CC (B-C)	E	456.40	458.90	454.70	460.00	460.50	529.50
BULK SG (A/E)	F	2.38	2.34	2.36	2.37	2.36	2.27
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	3.93	5.50	4.72	4.43	4.97	8.45
VOL AIR VOIDS (HE/100)	I	17.93	25.23	21.47	20.36	22.88	44.74
AVERAGE AIR VOIDS		5			6		
SATURATED							
SSD MASS, g	B'	1100.70	1095.30	1091.20			
MASS IN WATER, g	C'	644.14	636.10	636.38			
VOLUME, CC (B-C)	E'	456.56	459.20	454.82			
VOL ABS WATER, CC (B'-A) J'		13.30	19.80	16.80			
% SATURATION (100J'/I)		74.17	78.48	78.23			
% SWELL (100(E'-E)/E)		0.04	0.07	0.03			
AVERAGE SATURATION		76.96					
AVERAGE SWELL		0.04					
CONDITIONED							
THICKNESS, mm	t''	62.90	63.70	63.00			
SSD MASS, g	B''	1103.10	1098.10	1093.60			
MASS IN WATER, g	C''	645.40	637.30	637.10			
VOLUME, CC (B''-C'')	E''	457.70	460.80	456.50			
VOL ABS WATER, CC (B'-A) J''		15.70	22.60	19.20			
% SATURATION (100J''/I)		87.55	89.57	89.41			
% SWELL (100(E'-E)/E)		0.28	0.41	0.40			
AVERAGE SATURATION		88.84					
AVERAGE SWELL		0.36					
TENSILE STRENGTH							
LOAD, N	P	1071.86	777.84	887.67	1200.48	1058.12	1099.97
DRY STR (2000P/(T*D*3.14) Std					0.12	0.11	0.10
WET STR (2000P/(T*D*3.14) Stm		0.11	0.08	0.09			
AVG DRY STR (kpa):		0.112	AVG WET STR (kpa):		0.096	TSR, %	85.1
REMARKS:							

MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		SM2	
TENSILE STRENGTH RATIO				TEST METHOD		AASHTO	
SAMPLE		7	11	17	10	13	15
DIAMETER, mm	D	96.40	96.70	96.40	96.80	96.50	96.70
THICKNESS, mm	t	64.30	64.10	63.90	64.30	63.20	64.10
DRY MASS, g	A	1035.90	1044.40	1063.00	1046.50	1044.00	1052.40
SSD MASS, g	B	1036.90	1045.40	1063.80	1047.70	1045.10	1053.10
MASS IN WATER, g	C	574.00	584.10	605.30	584.20	589.60	594.00
VOLUME,CC (B-C)	E	462.90	461.30	458.50	463.50	455.50	459.10
BULK SG (A/E)	F	2.24	2.26	2.32	2.26	2.29	2.29
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	9.76	8.71	6.51	8.96	7.58	7.57
VOL AIR VOIDS (HE/100)	I	45.20	40.17	29.87	41.52	34.53	34.75
AVERAGE AIR VOIDS		8			8		
SATURATED							
SSD MASS, g	B'	1071.00	1077.10	1084.10			
MASS IN WATER, g	C'	608.20	615.80	625.50			
VOLUME,CC (B-C)	E'	462.80	461.30	458.60			
VOL ABS WATER, CC (B'-A)	J'	35.10	32.70	21.10			
% SATURATION (100J'/I)		77.66	81.40	70.64			
% SWELL (100(E'-E)/E)		-0.02	0.00	0.02			
AVERAGE SATURATION		76.57					
AVERAGE SWELL		0.00					
CONDITIONED							
THICKNESS, mm	t"	64.30	64.10	63.90			
SSD MASS, g	B"	1075.20	1080.00	1088.90			
MASS IN WATER, g	C"	610.60	616.80	628.20			
VOLUME,CC (B"-C")	E"	464.60	463.20	460.70			
VOL ABS WATER, CC (B'-A)	J"	39.30	35.60	25.90			
% SATURATION (100J'/I)		86.95	88.62	86.71			
% SWELL (100(E'-E)/E)		0.37	0.41	0.48			
AVERAGE SATURATION		87.43					
AVERAGE SWELL		0.42					
TENSILE STRENGTH							
LOAD, N	P	410.77	480.27	631.04	863.05	940.87	945.32
DRY STR (2000P/(T*D*3.14)	Std				0.09	0.10	0.10
WET STR (2000P/(T*D*3.14)	Strm	0.04	0.05	0.07			
AVG DRY STR (kpa):		0.095	AVG WET STR (kpa):		0.052	TSR, %	55.3
REMARKS:							

APPENDIX 4

Surface Cracks

MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		Mix1	
Surface Cracks		TEST METHOD				ASTM D4867	
SAMPLE		88	89	90	85	86	87
DIAMETER, mm	D	96.20	96.30	96.20	96.30	96.20	96.30
THICKNESS, mm	t	63.30	63.90	64.00	63.60	63.90	63.60
DRY MASS, g	A	1069.2	1069.2	1066.9	1069.7	1064	1073.3
SSD MASS, g	B	1069.9	1069.9	1067.4	1070.3	1064.6	1073.9
MASS IN WATER, g	C	611.2	607.6	605.7	610.1	603.1	615.2
VOLUME,CC (B-C)	E	458.7	462.3	461.7	460.2	461.5	458.7
BULK SG (A/E)	F	2.33	2.31	2.31	2.32	2.31	2.34
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	6.01	6.74	6.82	6.27	7.04	5.65
VOL AIR VOIDS (HE/100)	I	27.57	31.17	31.50	28.87	32.47	25.92
AGE AIR VOIDS		7			6		
SATURATED							
SSD MASS, g	B'	1131.00	1124.50	1122.30			
MASS IN WATER, g	C'	664.13	661.24	659.27			
VOLUME,CC (B-C)	E'	466.87	463.26	463.03			
VOL ABS WATER, CC (B'-A) J'		61.80	55.30	55.40			
% SATURATION (100J'/I)		224.15	177.41	175.88			
% SWELL (100(E'-E)/E)		1.78	0.21	0.29			
AVERAGE SATURATION		192.48					
AVERAGE SWELL		0.76					
CONDITIONED							
THICKNESS, mm	t"	63.30	63.90	64.00			
SSD MASS, g	B"	1138.80	1176.80	1074.20			
MASS IN WATER, g	C"	651.10	671.60	613.80			
VOLUME,CC (B"-C")	E"	487.70	505.20	460.40			
VOL ABS WATER, CC (B'-A) J"		69.60	107.60	7.30			
% SATURATION (100J'/I)		252.44	345.19	23.18			
% SWELL (100(E'-E)/E)		6.32	9.28	-0.28			
AVERAGE SATURATION		206.94					
AVERAGE SWELL		5.11					
PILE STRENGTH							
LOAD, N	P	1136.43	1339.38	1357.57	1840.40	1944.05	1838.44
DRY STR (2000P/(T*D*3.14) Std					0.19	0.20	0.19
WET STR (2000P/(T*D*3.14) Str		0.12	0.14	0.14			
STR (kpa):		0.195	WET STR (kpa):		0.133	TSR, %	68.1
REMARKS:							

MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		Mib2	
Surface Cracks		TEST METHOD				ASTM D4867	
SAMPLE		44	45	46	41	42	43
DIAMETER, mm	D	96.40	96.40	96.40	96.40	96.40	96.40
THICKNESS, mm	t	64.10	63.90	64.10	64.00	63.90	63.50
DRY MASS, g	A	1078.3	1067.8	1073.2	1079.7	1056	1056.3
SSD MASS, g	B	1079.1	1068.4	1074.5	1080.5	1056.7	1057
MASS IN WATER, g	C	615.8	609.8	613.2	617.6	593.7	594.7
VOLUME, CC (B-C)	E	463.3	458.6	461.3	462.9	463	462.3
BULK SG (A/E)	F	2.33	2.33	2.33	2.33	2.28	2.28
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	6.15	6.11	6.19	5.95	8.03	7.87
VOL AIR VOIDS (HE/100)	I	28.50	28.04	28.56	27.54	37.19	36.37
AGE AIR VOIDS		6			7		
SATURATED							
SSD MASS, g	B'	1098.72	1091.20	1098.12			
MASS IN WATER, g	C'	623.94	631.79	621.84			
VOLUME, CC (B-C)	E'	474.78	459.41	476.28			
VOL ABS WATER, CC (B'-A) J'		20.42	23.40	24.92			
% SATURATION (100J'/I)		71.65	83.47	87.26			
% SWELL (100(E'-E)/E)		2.48	0.18	3.25			
AVERAGE SATURATION		80.79					
AVERAGE SWELL		1.97					
CONDITIONED							
THICKNESS, mm	t"	64.10	63.90	64.10			
SSD MASS, g	B"	1138.80	1176.80	1074.20			
MASS IN WATER, g	C"	651.10	671.60	613.80			
VOLUME, CC (B"-C")	E"	487.70	505.20	460.40			
VOL ABS WATER, CC (B'-A) J"		60.50	109.00	1.00			
% SATURATION (100J'/I)		212.27	388.79	3.50			
% SWELL (100(E'-E)/E)		5.27	10.16	-0.20			
AVERAGE SATURATION		201.62					
AVERAGE SWELL		5.08					
PILE STRENGTH							
LOAD, N	P	978.73	905.38	809.34	2021.14	2132.06	2058.56
DRY STR (2000P/(T*D*3.14) Std					0.21	0.22	0.21
WET STR (2000P/(T*D*3.14) Str		0.10	0.09	0.08			
STR (kpa):		0.214	WET STR (kpa):	0.093	TSR, %	43.2	
REMARKS:							

MOISTURE INDUCED DAMAGE ANALYSIS					MIX TYPE		Mix I
Surface Cracks		TEST METHOD			AASHTO		
SAMPLE		94	95	96	91	92	93
DIAMETER, mm	D	96.20	95.10	95.90	96.10	96.10	93.80
THICKNESS, mm	t	63.90	63.90	63.70	63.90	63.60	63.60
DRY MASS, g	A	1059.90	1071.40	1065.40	1071.50	1069.80	1054.00
SSD MASS, g	B	1060.50	1072.30	1066.00	1072.10	1070.50	1054.70
MASS IN WATER, g	C	600.30	610.30	605.60	610.50	610.10	596.70
VOLUME, CC (B-C)	E	460.20	462.00	460.40	461.60	460.40	458.00
BULK SG (A/E)	F	2.30	2.32	2.31	2.32	2.32	2.30
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	7.13	6.49	6.69	6.40	6.31	7.21
VOL AIR VOIDS (HE/100)	I	32.82	29.98	30.80	29.54	29.03	33.00
AVERAGE AIR VOIDS		7			7		
SATURATED							
SSD MASS, g	B'	1094.85	1093.98	1094.44			
MASS IN WATER, g	C'	643.26	640.62	634.51			
VOLUME, CC (B-C)	E'	451.59	453.36	459.93			
VOL ABS WATER, CC (B'-A) J'		34.95	22.58	29.04			
% SATURATION (100J/I)		106.49	75.31	94.28			
% SWELL (100(E'-E)/E)		-1.87	-1.87	-0.10			
AVERAGE SATURATION		92.02					
AVERAGE SWELL		-1.28					
CONDITIONED							
THICKNESS, mm	t"	63.90	63.90	63.70			
SSD MASS, g	B"	1181.60	1219.80	1162.50			
MASS IN WATER, g	C"	680.50	701.80	667.10			
VOLUME, CC (B"-C")	E	501.10	518.00	495.40			
VOL ABS WATER, CC (B'-A) J"		121.70	148.40	97.10			
% SATURATION (100J/I)		370.80	494.93	315.23			
% SWELL (100(E'-E)/E)		8.89	12.12	7.60			
AVERAGE SATURATION		393.65					
AVERAGE SWELL		9.54					
TENSILE STRENGTH							
LOAD, N	P	1559.05	1323.67	1175.37	2122.17	2061.00	1985.24
DRY STR (2000P/(T*D*3.14) Std					0.22	0.21	0.21
WET STR (2000P/(T*D*3.14) Std		0.16	0.14	0.12			
AVG DRY STR (kpa):	0.216	WET STR (kpa):		0.141	TSR, %	65.4	
REMARKS:							

MOISTURE INDUCED DAMAGE ANALYSIS MIX TYPE						Mix2	
Surface Cracks				TEST METHOD		AASHTO	
SAMPLE		58	59	60	47	48	57
DIAMETER, mm	D	96.50	96.60	96.50	96.60	96.60	96.50
THICKNESS, mm	t	63.90	63.70	63.50	63.90	63.80	63.50
DRY MASS, g	A	1101.10	1103.40	1107.20	1049.40	1045.90	1089.90
SSD MASS, g	B	1102.00	1104.20	1107.80	1050.00	1046.90	1090.70
MASS IN WATER, g	C	637.30	641.20	645.10	587.40	583.50	630.60
VOLUME, CC (B-C)	E	464.70	463.00	462.70	462.60	463.40	460.10
BULK SG (A/E)	F	2.37	2.38	2.39	2.27	2.26	2.37
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	4.46	3.91	3.51	8.53	8.99	4.48
VOL AIR VOIDS (HE/100)	I	20.71	18.08	16.25	39.45	41.67	20.62
AVERAGE AIR VOIDS		4			7		
SATURATED							
SSD MASS, g	B'	1090.29	1099.80	1088.53			
MASS IN WATER, g	C'	636.55	640.05	630.35			
VOLUME, CC (B-C)	E'	453.74	459.75	458.18			
VOL ABS WATER, CC (B'-A) J'		-10.81	-3.60	-18.67			
% SATURATION (100J'/I)		-52.20	-19.91	-114.90			
% SWELL (100(E'-E)/E)		-2.36	-0.70	-0.98			
AVERAGE SATURATION		-62.34					
AVERAGE SWELL		-1.35					
CONDITIONED							
THICKNESS, mm	t''	63.90	63.70	63.50			
SSD MASS, g	B''	1181.80	1219.80	1162.50			
MASS IN WATER, g	C''	680.50	701.80	667.10			
VOLUME, CC (B''-C'')	E''	501.10	518.00	495.40			
VOL ABS WATER, CC (B''-A) J''		80.50	116.40	55.30			
% SATURATION (100J''/I)		388.74	643.78	340.34			
% SWELL (100(E''-E)/E)		7.83	11.88	7.07			
AVERAGE SATURATION		457.62					
AVERAGE SWELL		8.93					
TENSILE STRENGTH							
LOAD, N	P	1289.16	1263.56	1177.84	1771.91	1873.44	2023.61
DRY STR (2000P/(T'D*3.14) Std					0.18	0.19	0.21
WET STR (2000P/(T'D*3.14) Std		0.13	0.13	0.12			
AVG DRY STR (kpa):	0.196	WET STR (kpa):		0.129	TSR, %	65.8	
REMARKS:							

MOISTURE INDUCED DAMAGE ANALYSIS					MIX TYPE		HL1
Surface Cracks					TEST METHOD		MTO
		CONDITIONED			UNCONDITIONED		
SAMPLE		82	83	84	79	80	81
DRY MASS, g	A	1073.5	1080.1	1067.2	1080.5	1057.4	1067.5
SSD MASS, g	B	1074.2	1080.7	1067.8	1081.1	1058.2	1068.2
MASS IN WATER, g	C	612.7	618.6	609.2	620.5	604	607.9
VOLUME, CC (B-C)	E	461.5	462.1	458.6	460.6	454.2	460.3
BULK SG (A/E)	F	2.33	2.34	2.33	2.35	2.33	2.32
AVERAGE BULK SG		2.33			2.33		
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	6.21	5.75	6.17	5.41	6.13	6.49
AVERAGE AIR VOIDS		6.04			6.01		
STABILITY		4763.49	4315.25	4313.35	5993.59	5368	6058.17
CORRECTION FACTOR		1.19	1.19	1.19	1.19	1.19	1.19
CORRECTD STABILITY		5668.55	5135.15	5132.89	7132.37	6387.92	7209.22
AVERAGE STABILITY		5312.2			6909.8		
RETAINED STABILITY		76.9					
REMARKS:							
MOISTURE INDUCED DAMAGE ANALYSIS					MIX TYPE		HL1M
Surface Cracks					TEST METHOD		MTO
		CONDITIONED			UNCONDITIONED		
SAMPLE		38	39	40	35	36	37
DRY MASS, g	A	1073.6	1075.3	1076.7	1074.7	1073.8	1079.7
SSD MASS, g	B	1074.5	1075.9	1077.5	1075.4	1074.6	1080.6
MASS IN WATER, g	C	613.9	614.5	617.1	614.2	614.3	617.9
VOLUME, CC (B-C)	E	460.6	461.4	460.4	461.2	460.3	462.7
BULK SG (A/E)	F	2.33	2.33	2.34	2.33	2.33	2.33
AVERAGE BULK SG		2.33			2.33		
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	6.01	6.03	5.70	6.04	5.93	5.91
AVERAGE AIR VOIDS		5.91			5.96		
STABILITY		3640.85	3808.86	3963.48	5478.34	5779.28	6192.13
CORRECTION FACTOR		1.19	1.19	1.19	1.19	1.19	1.19
CORRECTD STABILITY		4332.61	4532.54	4716.54	6519.22	6877.34	7368.63
AVERAGE STABILITY		4527.2			6921.7		
RETAINED STABILITY		65.4					

MOISTURE INDUCED DAMAGE ANALYSIS						MIX TYPE		HL1	
Surface Cracks						TEST METHOD		PWGSC	
		CONDITIONED				UNCONDITIONED			
SAMPLE		71	72	73	74	75	76	77	78
DRY MASS, g	A	1052.9	1056.1	1069	1055.8	1068.2	1072.9	1069.5	1072.8
SSD MASS, g	B	1053.6	1056.8	1070	1056.5	1068.8	1073.7	1070.2	1073.5
MASS IN WATER, g	C	594.1	596	609.1	599.5	608.2	611.3	612	613.2
VOLUME, CC (B-C)	E	459.5	460.8	461.0	457.0	460.6	462.4	458.2	460.3
BULK SG (A/E)	F	2.29	2.29	2.32	2.31	2.32	2.32	2.33	2.33
AVERAGE BULK SG		2.30				2.33			
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	7.60	7.59	6.46	6.84	6.49	6.44	5.88	6.02
AVERAGE AIR VOIDS		7.12				6.21			
STABILITY		664.55	647.83	597.1	632.96	924.56	824.64	1108.34	967.96
CORRECTION FACTOR		1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19
CORRECTD STABILITY		790.8	770.9	710.5	753.2	1100.2	981.3	1318.9	1151.9
AVERAGE STABILITY		758.4				1138.1			
RETAINED STABILITY		66.5							
REMARKS:									
MOISTURE INDUCED DAMAGE ANALYSIS						MIX TYPE		HL1M	
Surface Cracks						TEST METHOD		PWGSC	
		CONDITIONED				UNCONDITIONED			
SAMPLE		27	28	29	30	31	32	33	34
DRY MASS, g	A	1082.8	1076	1101	1095.6	1097.9	1093	1085.3	1079.7
SSD MASS, g	B	1083.3	1076.5	1102	1096.1	1098.5	1093.6	1086.1	1080.5
MASS IN WATER, g	C	624.4	618.3	640.4	634.9	634.5	631.6	623.4	618.7
VOLUME, CC (B-C)	E	458.9	458.2	461.7	461.2	464.0	462.0	462.7	461.8
BULK SG (A/E)	F	2.36	2.35	2.39	2.38	2.37	2.37	2.35	2.34
AVERAGE BULK SG		2.37				2.35			
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	4.86	5.31	3.81	4.21	4.59	4.60	5.42	5.72
AVERAGE AIR VOIDS		4.55				5.08			
STABILITY		518.66	487.69	464.1	569	617.2	620.16	550.17	613
CORRECTION FACTOR		1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19
CORRECTD STABILITY		617.2	580.4	552.2	677.1	734.5	738.0	654.7	729.5
AVERAGE STABILITY		606.7				714.2			
RETAINED STABILITY		85.0							
REMARKS:									

TENSILE STRENGTH RATIO		TEST METHOD				Local	Mix1
SAMPLE		1	2	3	29	31	32
DIAMETER, mm	D	96.50	96.40	96.40	96.40	96.90	96.60
THICKNESS, mm	t	63.40	63.30	62.40	63.30	63.20	63.10
		CONDITIONED				Dry	
TENSILE STRENGTH							
LOAD, N	P	5954.00	6784.00	5972.00	8800.00	8742.00	9705.00
DRY STR (2000P/(T*D*3.14) Std					0.9185	0.9092	1.0141
WET STR (2000P/(T*D*3.14) Stm		0.6199	0.7081	0.6324			
AVG DRY STR (Mpa)	0.9473	AVG WET STR (M		0.6534	TSR, %	69.0	
TENSILE STRENGTH RATIO		TEST METHOD				Local	Mix2
SAMPLE		31	32	33	19	20	21
DIAMETER, mm	D	96.80	97.10	96.60	96.80	97.00	96.80
THICKNESS, mm	t	63.30	64.00	62.80	63.00	64.10	63.40
		CONDITIONED				Dry	
TENSILE STRENGTH							
LOAD, N	P	2619.00	2898.00	3805.00	6300.00	6120.00	6110.00
DRY STR (2000P/(T*D*3.14) Std					0.6580	0.6269	0.6341
WET STR (2000P/(T*D*3.14) Stm		0.2722	0.2970	0.3995			
AVG DRY STR (Mpa)	0.6397	AVG WET STR (M		0.3229	TSR, %	50.5	

TENSILE STRENGTH RATIO		TEST METHOD				Local	Mix1
SAMPLE		4	5	6	33	34	35
DIAMETER, mm	D	96.50	96.70	96.30	97.10	97.00	96.70
THICKNESS, mm	t	63.00	63.20	63.30	62.70	63.40	63.80
		CONDITIONED				Dry	
TENSILE STRENGTH							
LOAD, N	P	6841.00	6578.00	7029.00	9857.00	8893.00	8019.00
DRY STR (2000P/(T*D*3.14) Std					1.0103	1.0245	0.9311
WET STR (2000P/(T*D*3.14) Stm		0.7187	0.6856	0.7345			
AVG DRY STR (Mpa):	0.9887	AVG WET STR (Mpa):		0.7122	TSR, %	72.0	
TENSILE STRENGTH RATIO		TEST METHOD				Local	Mix2
SAMPLE		16	17	18	22	23	24
DIAMETER, mm	D	96.60	96.60	96.50	96.60	96.60	96.50
THICKNESS, mm	t	63.60	62.70	63.50	62.50	63.50	62.90
		CONDITIONED				Dry	
TENSILE STRENGTH							
LOAD, N	P	5063.00	4373.00	3383.00	6137.00	6286.00	7453.00
DRY STR (2000P/(T*D*3.14) Std					0.8474	0.6527	0.7821
WET STR (2000P/(T*D*3.14) Stm		0.5249	0.4599	0.3518			
AVG DRY STR (Mpa):	0.6941	AVG WET STR (Mpa):		0.4455	TSR, %	64.2	

Air Voids Effet

MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		Mixl	
TENSILE STRENGTH RATIO				TEST METHOD		LOCAL	
SAMPLE		100/1	100/2	100/3	100/4	100/5	100/6
DIAMETER, mm	D	101.60	101.60	101.60	101.70	101.60	101.70
THICKNESS, mm	t	56.40	58.80	54.10	57.40	55.60	55.10
DRY MASS, g	A	1107.19	1049.38	1055.51	1126.57	1188.21	1067.79
SSD MASS, g	B	1108.16	1050.15	1056.22	1127.56	1189.01	1068.59
MASS IN WATER, g	C	658.06	619.06	625.97	667	695.31	629.82
VOLUME, CC (B-C)	E	450.10	431.09	430.25	460.56	493.70	438.77
BULK SG (A/E)	F	2.46	2.43	2.45	2.45	2.41	2.43
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	0.93	1.96	1.20	1.49	3.07	1.99
VOL AIR VOIDS (HE/100)	I	4.19	8.46	5.16	6.85	15.16	8.73
AGE AIR VOIDS		1.4			2.2		
TENSILE STRENGTH		CONDITIONED			UNCONDITIONED		
LOAD, N	P	2614.26	2286.22	2470.91	2788.70	2905.41	2585.20
DRY STR (2000P/(T*D*3.14) Std					0.30	0.33	0.29
WET STR (2000P/(T*D*3.14) Stm		0.29	0.24	0.29			
STR (kpa):	0.308	WET STR (kpa):		0.274	TSR, %		88.7
REMARKS:							
MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		Mixl	
TENSILE STRENGTH RATIO				TEST METHOD		LOCAL	
SAMPLE		60/1	61/2	60/3	60/4	60/5	60/6
DIAMETER, mm	D	101.60	101.70	101.60	101.60	101.60	101.50
THICKNESS, mm	t	55.60	53.60	54.40	57.30	58.60	54.60
DRY MASS, g	A	1070.52	1032.04	1054.29	1109.8	1133.91	1065.39
SSD MASS, g	B	1071.27	1033.1	1055.33	1111.25	1134.94	1066.12
MASS IN WATER, g	C	629.19	609.63	619.98	655.12	667.1	628.29
VOLUME, CC (B-C)	E	442.08	423.47	435.35	456.13	467.84	437.83
BULK SG (A/E)	F	2.42	2.44	2.42	2.43	2.42	2.43
MAX SG	G	2.48	2.48	2.48	2.48	2.48	2.48
% AIR VOIDS (100(G-F)/G)	H	2.47	1.85	2.47	2.01	2.39	2.00
VOL AIR VOIDS (HE/100)	I	10.94	7.83	10.75	9.17	11.17	8.76
AGE AIR VOIDS		2.3			2.1		
TENSILE STRENGTH		CONDITIONED			UNCONDITIONED		
LOAD, N	P	2515.29	2559.56	2410.83	2716.73	3088.97	3044.54
DRY STR (2000P/(T*D*3.14) Std					0.30	0.33	0.35
WET STR (2000P/(T*D*3.14) Stm		0.28	0.30	0.28			
STR (kpa):	0.326	WET STR (kpa):		0.287	TSR, %		87.9
REMARKS:							

MOISTURE INDUCED DAMAGE ANALYSIS MIX TYPE						Mix3		
TENSILE STRENGTH RATIO			TEST METHOD			LOCAL		
SAMPLE			12/1.	12/2.	12/3.	12/4.	12/5.	12/6.
DIAMETER, mm	D		101.50	101.60	101.50	101.50	101.50	101.60
THICKNESS, mm	t		58.60	58.30	63.50	67.90	65.50	61.00
DRY MASS, g	A		1008.00	1026.49	1132.69	1196.50	1183.17	1092.95
SSD MASS, g	B		1027.50	1037.95	1143.28	1210.70	1193.15	1101.95
MASS IN WATER, g	C		584.36	584.80	645.24	691.52	677.49	623.49
VOLUME,CC (B-C)	E		443.14	453.15	498.04	519.18	515.66	478.46
BULK SG (A/E)	F		2.27	2.27	2.27	2.30	2.29	2.28
MAX SG	G		2.52	2.52	2.52	2.52	2.52	2.52
% AIR VOIDS (100(G-F)/G)	H		9.66	10.04	9.68	8.48	8.88	9.28
VOL AIR VOIDS (HE/100)	I		42.82	45.49	48.20	44.00	45.78	44.41
AVERAGE AIR VOIDS			9.8			8.9		
TENSILE STRENGTH			CONDITIONED			UNCONDITIONED		
LOAD, N	P		1956.73	1942.41	1995.04	2499.53	2424.65	2162.59
DRY STR (2000P/(T*D*3.14))	Std					0.23	0.23	0.22
WET STR (2000P/(T*D*3.14))	Stm		0.21	0.21	0.20			
AVG DRY STR (kpa):			0.229	WET STR (kpa):		0.205	TSR, %	89.8
REMARKS:								
MOISTURE INDUCED DAMAGE ANALYSIS MIX TYPE						Mix3		
TENSILE STRENGTH RATIO			TEST METHOD			LOCAL		
SAMPLE			6/1.	6/2.	6/3.	6/4.	6/5.	6/6.
DIAMETER, mm	D		101.70	101.60	101.60	101.60	101.60	101.70
THICKNESS, mm	t		64.80	61.70	62.40	60.40	63.30	60.90
DRY MASS, g	A		1093.23	1036.15	1042.77	1029.57	1069.01	977.75
SSD MASS, g	B		1113.71	1078.72	1060.63	1044.85	1084.15	1015.75
MASS IN WATER, g	C		618.06	604.39	595.90	581.81	607.60	562.50
VOLUME,CC (B-C)	E		495.65	474.33	464.73	463.04	476.55	453.25
BULK SG (A/E)	F		2.21	2.18	2.24	2.22	2.24	2.16
MAX SG	G		2.52	2.52	2.52	2.52	2.52	2.52
% AIR VOIDS (100(G-F)/G)	H		12.40	13.25	10.89	11.70	10.91	14.33
VOL AIR VOIDS (HE/100)	I		61.48	62.83	50.60	54.16	52.00	64.95
AVERAGE AIR VOIDS			12.2			12.3		
TENSILE STRENGTH			CONDITIONED			UNCONDITIONED		
LOAD, N	P		1403.94	1618.17	1330.59	1820.16	1639.93	1518.72
DRY STR (2000P/(T*D*3.14))	Std					0.19	0.16	0.18
WET STR (2000P/(T*D*3.14))	Stm		0.14	0.16	0.13			
AVG DRY STR (kpa):			0.169	WET STR (kpa):		0.145	TSR, %	85.5
REMARKS:								

MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		Mixer	
Air Voids Effect at 60 C				TEST METHOD		LOCAL	
SAMPLE		100/1	100/3	100/5	100/2	100/4	100/6
DIAMETER, mm	D	101.60	101.60	101.60	101.60	101.50	101.70
THICKNESS, mm	t	65.70	62.50	60.90	67.10	62.10	58.40
DRY MASS, g	A	1219.28	1155.36	1130.7	1239.63	1148.39	1088.82
SSD MASS, g	B	1221.13	1156.35	1131.74	1240.22	1149.18	1089.75
MASS IN WATER, g	C	695.63	657.66	645.7	705.36	653.65	622.7
VOLUME, CC (B-C)	E	525.5	498.69	486.04	534.86	495.53	467.05
BULK SG (A/E)	F	2.32	2.32	2.33	2.32	2.32	2.33
MAX SG	G	2.44	2.44	2.44	2.44	2.44	2.44
% AIR VOIDS (100(G-F)/G)	H	4.91	5.05	4.66	5.01	5.02	4.46
VOL AIR VOIDS (HE/100)	I	25.80	25.18	22.64	26.81	24.88	20.81
AGE AIR VOIDS		4.9			4.8		
FILE STRENGTH		CONDITIONED			UNCONDITIONED		
LOAD, N	P	4901.47	4444.28	4785.69	5241.37	5184.23	4774.84
DRY STR (2000P/(T*D*3.14) Std					0.49	0.52	0.51
WET STR (2000P/(T*D*3.14) Stm		0.47	0.45	0.49			
STR (kpa):		0.509		WET STR (kpa):	0.469		TSR, %
REMARKS:							
MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		Mixer	
Air Voids Effect at 60 C				TEST METHOD		LOCAL	
SAMPLE		60/1	61/3	60/5	60/2	60/4	60/6
DIAMETER, mm	D	101.70	101.50	101.50	101.70	101.70	101.60
THICKNESS, mm	t	57.20	58.00	63.00	57.80	57.60	55.80
DRY MASS, g	A	1038.47	1066.88	1144	1055.38	1050.44	1011.89
SSD MASS, g	B	1039.91	1068.36	1146.79	1057.22	1052.73	1014.62
MASS IN WATER, g	C	585.24	605.89	644.2	596.84	593.13	569.82
VOLUME, CC (B-C)	E	454.67	462.47	502.59	460.38	459.6	444.8
BULK SG (A/E)	F	2.28	2.31	2.28	2.29	2.29	2.27
MAX SG	G	2.44	2.44	2.44	2.44	2.44	2.44
% AIR VOIDS (100(G-F)/G)	H	6.39	5.45	6.71	6.05	6.33	6.77
VOL AIR VOIDS (HE/100)	I	29.07	25.22	33.74	27.85	29.09	30.09
AGE AIR VOIDS		6.2			6.4		
TENSILE STRENGTH		CONDITIONED			UNCONDITIONED		
LOAD, N	P	3795.10	4106.34	4806.66	4087.65	4226.10	4971.67
DRY STR (2000P/(T*D*3.14) Std					0.44	0.46	0.56
WET STR (2000P/(T*D*3.14) Stm		0.42	0.44	0.48			
STR (kpa):		0.487		WET STR (kpa):	0.440		TSR, %
REMARKS:							
MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		Mixer	
Air Voids Effect				TEST METHOD		LOCAL	
SAMPLE		200/1	200/2	200/3	200/4	200/5	200/6
DIAMETER, mm	D	101.60	102.00	101.80	101.80	101.80	101.70
THICKNESS, mm	t	56.8	51.4	51.7	43.6	53.8	53.9
DRY MASS, g	A	1045.1	958.6	940.6	806.4	989.8	993.9
SSD MASS, g	B	1045.7	959.3	941.1	806.9	990.8	994.9
MASS IN WATER, g	C	595.8	549.9	530.8	459.9	561.5	566.1
VOLUME, CC (B-C)	E	449.9	409.4	410.3	347	429.3	428.8
BULK SG (A/E)	F	2.32	2.34	2.29	2.32	2.31	2.32
MAX SG	G	2.44	2.44	2.44	2.44	2.44	2.44
% AIR VOIDS (100(G-F)/G)	H	4.80	4.04	6.05	4.76	5.51	5.01
VOL AIR VOIDS (HE/100)	I	21.58	16.53	24.81	16.51	23.64	21.46
AGE AIR VOIDS		5.0			5.1		
FILE STRENGTH		CONDITIONED			UNCONDITIONED		
LOAD, N	P	3124.62	3003.46	2498.05	3284.23	4185.23	4341.34
DRY STR (2000P/(T*D*3.14) Std					0.47	0.49	0.50
WET STR (2000P/(T*D*3.14) Stm		0.35	0.36	0.30			
STR (kpa):		0.487		WET STR (kpa):	0.338		TSR, %
REMARKS:							

MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		M ₅₅	
Air Voids Effect at 60 C				TEST METHOD		LOCAL	
SAMPLE		100/1	100/2	100/3	100/4	100/5	100/6
DIAMETER, mm	D	101.30	101.70	101.60	101.90	101.80	101.90
THICKNESS, mm	t	52.40	51.40	56.90	60.60	61.60	60.10
DRY MASS, g	A	970.5	951.7	1041.5	1138.6	1132.8	1118.6
SSD MASS, g	B	970.9	952.3	1042.3	1139.4	1133.6	1119.5
MASS IN WATER, g	C	560.3	547.8	598.1	656.7	648.4	645.6
VOLUME, CC (B-C)	E	410.60	404.50	444.20	482.70	485.20	473.90
BULK SG (A/E)	F	2.36	2.35	2.34	2.36	2.33	2.36
MAX SG	G	2.44	2.44	2.44	2.44	2.44	2.44
% AIR VOIDS (100(G-F)/G)	H	3.13	3.57	3.91	3.33	4.32	3.26
VOL AIR VOIDS (HE/100)	I	12.85	14.46	17.36	16.06	20.94	15.46
AGE AIR VOIDS		3.5			3.6		
TENSILE STRENGTH				CONDITIONED		UNCONDITIONED	
LOAD, N	P	3221.62	3078.27	3310.30	4403.91	3993.04	4095.07
DRY STR (2000P/(T*D*3.14) Std					0.46	0.41	0.43
WET STR (2000P/(T*D*3.14) Stm		0.39	0.38	0.36			
STR (kpa):	0.429	WET STR (kpa):		0.375	TSR, %	87.6	
REMARKS:							
MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		M ₅₅	
Air Voids Effect at 60 C				TEST METHOD		LOCAL	
SAMPLE		60/1	60/2	60/3	60/4	60/5	60/6
DIAMETER, mm	D	101.80	101.80	102.00	101.80	101.80	101.60
THICKNESS, mm	t	57.50	56.90	56.30	58.80	62.00	55.90
DRY MASS, g	A	1064.6	1057	1043.5	1084.5	1078.5	1051.9
SSD MASS, g	B	1066.1	1057.9	1044.3	1085.8	1083	1054.6
MASS IN WATER, g	C	608.1	606.5	597.5	621.5	618.5	604.8
VOLUME, CC (B-C)	E	458.00	451.40	446.80	464.30	464.50	449.80
BULK SG (A/E)	F	2.32	2.34	2.34	2.34	2.32	2.34
MAX SG	G	2.44	2.44	2.44	2.44	2.44	2.44
% AIR VOIDS (100(G-F)/G)	H	4.74	4.03	4.28	4.27	4.84	4.16
VOL AIR VOIDS (HE/100)	I	21.69	18.20	19.14	19.83	22.49	18.69
AGE AIR VOIDS		4.4			4.4		
TENSILE STRENGTH				CONDITIONED		UNCONDITIONED	
LOAD, N	P	3187.44	3100.95	3109.85	3908.42	4183.24	3520.30
DRY STR (2000P/(T*D*3.14) Std					0.42	0.42	0.39
WET STR (2000P/(T*D*3.14) Stm		0.34	0.37	0.38			
STR (kpa):	0.411	WET STR (kpa):		0.366	TSR, %	89.0	
REMARKS:							
WARM WATER TEMPERATURE 8hr and 80C							
MOISTURE INDUCED DAMAGE ANALYSIS				MIX TYPE		PENTACYON WITH AS	
TENSILE STRENGTH RATIO				TEST METHOD		LOCAL	
SAMPLE		40/1	40/2	40/3	40/4	40/5	40/6
DIAMETER, mm	D	101.70	101.60	101.10	101.70	101.70	101.60
THICKNESS, mm	t	51.70	64.10	55.00	57.40	50.80	65.10
DRY MASS, g	A	943.5	1156.1	951.2	1014.4	917.3	1176.8
SSD MASS, g	B	944.6	1157.9	954.1	1018.4	919.3	1178.5
MASS IN WATER, g	C	534.5	648.1	524.8	563.9	516.4	660.3
VOLUME, CC (B-C)	E	410.10	509.80	429.30	454.50	402.90	518.20
BULK SG (A/E)	F	2.30	2.27	2.22	2.23	2.28	2.27
MAX SG	G	2.44	2.44	2.44	2.44	2.44	2.44
% AIR VOIDS (100(G-F)/G)	H	5.71	7.06	9.19	8.53	6.69	6.93
VOL AIR VOIDS (HE/100)	I	23.42	35.99	39.46	38.76	26.96	35.90
AGE AIR VOIDS			7.3			7.4	
TENSILE STRENGTH				CONDITIONED		UNCONDITIONED	
LOAD, N	P	2381.29	3253.25	2116.74	3157.66	3554.69	3956.16
DRY STR (2000P/(T*D*3.14) Std					0.34	0.44	0.38
WET STR (2000P/(T*D*3.14) Stm		0.29	0.32	0.24			
STR (kpa):	0.388	WET STR (kpa):		0.283	TSR, %	73.0	
REMARKS:							

Warm Water Bath

Different warm Water Bath Duration and the TSR Surface Mix 1 (Laboratory Samples)								
Sample Number	Diameter mm	Height mm	Peak Load (N)	ITS (Mpa)	Average	Dis.	Duration	TSR %
1-new	101.80	58.70	3843.0	0.41	0.45	0.10	0.25	100
2-new	101.55	58.70	4683.0	0.50		0.09		
3-new	101.80	57.10	3960.0	0.43		0.11		
4	101.53	65.15	3810.4	0.37	0.38	0.10	0.50	86
5	101.68	56.35	3880.2	0.43		0.09		
6	101.70	59.43	3345.3	0.35		0.11		
7	101.68	59.40	3091.0	0.33	0.30	0.11	1.00	66
8	101.60	61.38	2562.4	0.26		0.12		
9	101.95	60.75	2902.2	0.30		0.09		
46	101.63	57.50	2216.1	0.24	0.25	0.10	2.00	57
47	101.63	51.13	2144.8	0.26		0.11		
48	101.55	52.65	2144.0	0.26		0.11		
43	101.38	52.08	1841.5	0.22	0.25	0.06	4.00	57
44	101.85	53.13	2104.5	0.25		0.08		
45	101.73	60.05	2816.7	0.29		0.08		
10	101.69	60.38	2400.3	0.25	0.24	0.13	6.00	54
11	101.73	62.18	1977.1	0.20		0.12		
14	101.83	58.78	2569.1	0.27		0.14		
15	101.40	58.50	1979.4	0.21	0.21	0.10	8.00	48
16	101.63	58.85	1917.9	0.20		0.11		
17	101.70	60.85	2168.0	0.22		0.10		
18	101.83	59.88	1786.6	0.19	0.19	0.13	24.00	43
19	101.63	62.00	2014.5	0.20		0.12		
20	101.70	58.31	1725.4	0.19		0.09		

Different warm Water Bath Duration and the TSR Surface Mix 1 (Field Samples)								
Sample Number	Diameter mm	Height mm	Peak Load (N)	ITS (Mpa)	Average	Dis.	Duration	TSR %
1-new	97.3	64.1	1591.5	0.16	0.167	0.09	0.25	100
2-new	96.3	63.4	1764.8	0.18		0.10		
3-new	96.1	64.1	1506.3	0.16		0.09		
71	96.35	63.7	879.5	0.09	0.097	0.09	0.5	58
72	96.325	64.025	874.8	0.09		0.10		
73	96.425	63.625	1061.3	0.11		0.09		
74	96.675	63.6	789.9	0.08	0.081	0.09	1	48
75	96.35	63.75	719.8	0.07		0.09		
76	96.5	64	832.2	0.09		0.11		
34	96.4	64.5	763.1	0.08	0.068	0.06	2	41
35	96.1	62.7	535.4	0.06		0.08		
43	96.2	63.6	666.9	0.07		0.06		
37	96.2	63.5	445.2	0.05	0.049	0.12	4	29
38	96.3	61.2	522.0	0.06				
46	96.4	63.9	423.2	0.04		0.10		
39	96.3	64.8	407.8	0.04	0.044	0.06	6	26
40	96.2	62.4	581.2	0.06		0.09		
48	96.2	63.4	271.9	0.03		0.07		
41	96.2	63.7	304.8	0.03	0.038	0.08	8	22
42	96.2	64.6	309.3	0.03		0.08		
44	96.3	63.5	473.8	0.05		0.07		
45	96.4	64	252.0	0.03	0.036	0.08	24	22
69	96.4	63.9	368.5	0.04		0.11		
70	96.7	63.6	429.8	0.04		0.13		

Different Warm Water Bath Duration and the TSR Surface Mix 2(Field Samples)								
Sample Number	Diameter mm	Height mm	Peak Load (N)	ITS (Mpa)	Average	Dis.	Duration	TSR %
1-new	96.60	64.10	1406.5	0.14	0.149	0.13	0.25	100
2-new	96.50	63.75	1564.9	0.16		0.12		
3-new	96.55	63.40	1348.9	0.14		0.09		
65	96.58	63.83	1037.1	0.11	0.091	0.13	0.5	61
66	96.80	63.35	839.6	0.09		0.12		
67	96.95	63.65	770.4	0.08		0.09		
47	96.60	63.90	833.0	0.09	0.072	0.09	1	48
89	98.10	63.20	541.6	0.06		0.10		
96	96.20	63.70	710.5	0.07		0.07		
52	96.50	63.68	346.6	0.04	0.045	0.09	2	30
53	96.50	63.73	454.0	0.05		0.07		
54	96.58	63.70	488.9	0.05		0.07		
55	96.53	63.60	459.8	0.05	0.054	0.08	4	36
56	96.85	63.65	535.9	0.06		0.08		
61	96.65	63.63	557.7	0.06		0.08		
62	96.58	63.60	467.2	0.05	0.047	0.08	6	31
63	96.63	63.35	449.9	0.05		0.08		
64	96.53	63.75	431.7	0.04		0.08		
65	96.58	63.83	209.0	0.02	0.020	0.08	8	14
66	96.80	63.35	182.2	0.02		0.12		
67	96.95	63.65	197.4	0.02		0.09		
68	97.13	63.13	167.5	0.02	0.018	0.06	24	12
69	96.90	63.48	176.3	0.02		0.10		
70	96.88	63.48	175.7	0.02		0.08		

Different warm Water Bath Duration and the TSR Surface Mix without antistripping agent (Mix4)									
Sample Number	Diameter mm	Hight mm	Peak Load (N)	ITS (Mpa)	Average	Dis.	Duration	TSR %	
1-new	101.63	60.55	3828.0	0.40	0.379	0.06	0.25	100	
2-new	101.63	62.63	4065.0	0.41		0.05			
3-new	101.58	55.00	2925.0	0.33		0.06			
4	101.43	54.05	2417.9	0.28	0.257	0.06	0.5	68	
5	101.63	59.43	2347.5	0.25		0.05			
6	101.58	59.88	2305.9	0.24		0.06			
7	101.70	60.53	1996.1	0.21	0.219	0.06	1	58	
8	101.43	59.73	2124.2	0.22		0.05			
9	101.51	59.00	2144.8	0.23		0.05			
10	101.53	59.68	2365.1	0.25	0.212	0.09	2		
11	101.35	53.00	1459.7	0.17		0.05			
12	101.55	60.88	2071.7	0.21		0.07			
13	101.45	55.05	1687.8	0.19	0.187	0.05	4	49	
14	101.25	63.15	1889.3	0.19		0.06			
15	101.78	63.93	1830.3	0.18		0.07			
16	101.60	60.93	1807.8	0.19	0.162	0.06	6	43	
17	101.75	61.10	1718.5	0.18		0.06			
18	101.83	63.70	1253.8	0.12		0.08			
19	101.60	59.50	1321.5	0.14	0.135	0.07	8	36	
20	101.23	59.10	1288.5	0.14		0.07			
21	101.58	63.90	1314.4	0.13		0.07			
22	101.55	60.50	1340.1	0.14	0.132	0.05	24	35	
23	101.53	66.68	1483.6	0.14		0.06			
24	101.53	60.65	1144.0	0.12		0.04			

Different warm Water Bath Duration and the TSR Surface Mix with antistripping agent (Mix5)								
Sample Number	Diameter mm	Hight mm	Peak Load (N)	ITS (Mpa)	Average	Dis.	Duration	TSR %
1-new	101.40	62.50	4325.0	0.43	0.35	0.06	0.25	100
2-new	101.55	61.50	3125.0	0.32		0.05		
3-new	101.55	60.30	2965.0	0.31		0.05		
4	101.40	60.63	2446.5	0.25	0.25	0.06	0.5	71
5	101.65	62.83	2630.4	0.26		0.05		
6	101.40	61.03	2303.7	0.24		0.05		
7	101.60	62.40	1808.1	0.18	0.20	0.04	1	56
8	101.50	62.15	1878.0	0.19		0.05		
9	101.20	61.20	2213.3	0.23		0.05		
10	101.65	60.88	1523.5	0.16	0.15	0.07	2	41
11	101.65	52.05	1350.6	0.16		0.06		
12	102.20	56.43	1078.7	0.12		0.06		
13	101.60	55.83	1339.6	0.15	0.14	0.06	4	41
14	101.60	54.50	1156.1	0.13		0.05		
15	101.65	57.73	1357.0	0.15		0.05		
16	101.60	54.43	1078.5	0.12	0.11	0.06	6	32
17	101.50	59.73	1113.5	0.12		0.07		
18	101.35	59.58	921.8	0.10		0.07		
19	101.45	62.18	1146.5	0.12	0.11	0.07	8	32
20	101.70	62.60	964.5	0.10		0.06		
21	101.55	59.10	1219.1	0.13		0.06		
22	101.75	58.60	894.8	0.10	0.10	0.06	24	27

Cooling Water Bath

The Cooling Duration effect on TSR for Laboratory Samples (Mix 1)						
Sample Number	Diameter mm	Hight mm	Peak Load (N)	ITS Mpa	Average	Cooling Duration
91	101.68	59.10	9722.0	1.03	0.99	15
92	101.65	59.28	10047.0	1.06		
93	101.70	62.20	8820.0	0.89		
62	101.95	63.70	11488.9	1.13	1.03	30
67	101.70	60.80	11014.1	1.13		
69	101.70	56.60	7613.1	0.84		
77	101.75	56.80	9388.7	1.03	1.08	60
79	101.60	58.50	10318.3	1.11		
80	101.60	57.40	10204.3	1.11		
82	101.83	60.70	10053.0	1.04	1.14	120
83	101.68	57.70	10333.4	1.12		
86	101.65	56.20	11335.4	1.26		
87	101.55	53.80	10988.1	1.28	1.21	180
88	101.68	51.70	9110.6	1.10		
89	101.63	57.50	11421.1	1.24		

The Cooling Duration effect on TSR for Field Cores (Mix 1)						
Sample Number	Diameter mm	Hight mm	Peak Load (N)	ITS Mpa	Average	Cooling Duration
26	96.50	63.8	680.0	0.07	0.07	15
50	96.50	63.8	832.5	0.09	0.08	30
51	86.60	63.4	700.5	0.08		
52	96.50	63.7	823.6	0.09		
56	96.90	63.7	950.3	0.10	0.11	60
57	96.50	63.5	971.4	0.10		
58	96.50	63.9	1132.1	0.12		
59	96.60	63.7	1118.2	0.12	0.11	120
60	96.50	63.5	1061.6	0.11		
61	96.70	63.6	978.3	0.10		
62	96.60	63.6	1195.6	0.12	0.14	180

The Cooling Duration effect on TSR for field cores Mix 2						
Sample Number	Diameter mm	Hight mm	Peak Load (N)	ITS Mpa	Average	Cooling Duration
48	96.70	63.90	2876.00	0.30	0.30	15
49	96.60	63.30	3005.00	0.31		
50	96.80	63.50	2756.00	0.29		
1	96.80	62.90	3066.00	0.32	0.35	30
2	96.50	63.80	3555.00	0.37		
3	96.50	63.60	3475.00	0.36		
4	96.80	63.50	3742.00	0.39	0.35	60
5	96.70	62.80	3241.00	0.34		
6	97.20	62.80	3136.00	0.33		
7	96.6	64.20	4026.00	0.41	0.37	120
8	96.6	63.40	3347.00	0.35		
9	96.4	63.30	3402.00	0.36		
10	97	63.60	Failed	#VALUE!	0.29	180
11	96	63.80	2469.90	0.26		
12	97	63.30	3108.00	0.32		
The Cooling Duration effect on TSR for Laboratory Samples Mix7						
Sample Number	Diameter mm	Hight mm	Peak Load (N)	ITS Mpa	Average	Cooling Duration
41	102.20	58.00	9230.00	0.99	0.82	15
42	102.70	62.50	5813.00	0.58		
43	102.20	62.1	8956.00	0.90		
5	102.70	64.10	9546.00	0.92	1.04	30
6	102.00	56.70	12629.00	1.39		
7	102.40	54.3	6998.00	0.80		
8	102.00	56.8	10652.00	1.17	1.17	60
9	102.20	55.4	10399.00	1.17		
4	101.60	64.70	12003.00	1.16		
10	102.50	63.30	13930.00	1.37	1.20	120
11	102.50	52.90	8380.00	0.98		
12	102.70	62.20	12436.00	1.24		
13	101.90	61.90	9306.00	0.94	1.11	180
14	102.20	54.50	5912.00	0.68		
15	101.90	69.50	19115.00	1.72		

Environmental Factors

The Effect of Degree of Saturation on the TSR Using Surface Mix 1									
Sample Number	Density	Average	Air Voids	Average	Peak Load	Average	Vacume Duration	% Sr.	TSR
21	2.41		2.8		3246.34			0	
22	2.42		2.4		2916.23			0	
23	2.40	2.41	3.2	2.79	3432.5	3198.36	0	0	100
24	2.42		2.3		3478.36			52	
25	2.39		3.6		3432.99			57	
26	2.42	2.41	2.5	2.82	3370.41	3427.25	30 min	57	100
27	2.38		4.0		3311.83			64	
28	2.41		2.9		3268.97			58	
29	2.37	2.39	4.3	3.76	2127.61	2902.80	45 mi	66	90.8
30	2.37		4.3		3532.51			89	
31	2.40		3.2		2582.25			87	
32	2.43	2.40	2.0	3.18	2582.25	2899.00	60 min	95	90.6
33	2.41		3.0		2562.02			100	
34	2.37		4.4		1970.91			93	
35	2.40	2.39	3.2	3.53	2338.88	2290.60	120 min	95	71.6
36	2.38		3.9		2249.31			101	
37	2.40		3.1		2623.7			103	
38	2.42	2.40	2.5	3.16	2159.15	2344.05	180 min	87	73.3

Freez-Thaw effect for Mix 2 Field

Freez-Thaw effect for Mix 6 Lab														
Sample#	Dav	Hav	Total Vol	Av	Vol Air	Wd	Wss	Dsr	Aver.	Freezing Duration	Peak Load (N)	ITS Mpa	Average	TSR %
22	103.55	56.45	461.0	7.14	32.92	988.80			0.00	0.00	6434.0	0.70	0.85	100
23	103.10	60.60	496.4	7.34	36.46	1068.18					7989.0	0.81		
24	102.70	56.75	482.1	8.10	39.05	1039.17					9428.0	1.03		
25	103.30	60.75	500.1	11.87	59.36	1066.90	1110.72	73.82	75.27	2.00	5116.0	0.52	0.51	60
26	102.80	61.25	498.1	8.57	42.70	1074.35	1101.17	62.82			6149.0	0.62		
27	104.15	55.20	461.1	7.84	36.15	978.73	1010.96	89.17			3504.0	0.39		
28	102.35	54.30	456.8	9.86	45.05	983.53	1009.80	58.31	57.85	4.00	7229.0	0.83	0.78	92
29	102.35	56.95	481.8	8.78	42.29	1038.29	1064.60	62.21			7357.0	0.80		
30	102.25	62.25	521.7	10.79	56.30	1121.62	1151.47	53.02			7046.0	0.71		
31	102.30	54.70	470.3	10.00	47.01	1005.45	1032.56	57.67	66.68	16.00	5651.0	0.64	0.75	89
32	102.60	55.60	450.7	11.00	49.57	995.73	1024.26	57.56			7578.0	0.85		
33	102.75	58.10	473.0	7.84	37.10	1036.40	1067.86	84.80			7249.0	0.77		
34	103.80	60.55	498.1	8.44	42.06	1076.61	1115.36	92.13	81.54	24.00	5293.0	0.54	0.69	135
35	102.80	60.20	503.7	7.99	40.25	1092.10	1121.91	74.06			9096.0	0.94		
36	102.20	58.75	490.7	7.51	36.85	1051.67	1080.57	78.43			5602.0	0.59		
37	103.00	53.95	441.3	7.12	31.42	934.18	955.70	68.49	67.37	48.00	5416.0	0.62	0.58	68
38	102.65	52.05	423.0	7.40	31.29	913.13	933.86	66.25			5393.0	0.64		
39	103.75	53.25	442.3	6.87	30.37	943.60	968.62	82.38			4131.0	0.48		
Freez-Thaw effect for Mix 7 - Lab														
Sample#	Dav	Hav	Total Vol	Av	Vol Air	Wd	Wss	Dsr	Aver.	Freezing Duration	Peak Load (N)	ITS Mpa	Average	TSR %
22	102.05	54.2	455.1	9.0	40.80	1020.3			0.00	0.00	13712.0	1.58	1.45	100
23	102.10	58.5	490.5	8.7	42.52	1097.4					12674.0	1.35		
24	102.40	59.8	500.1	8.5	42.56	1126.2					13744.4	1.43		
25	102.15	52.3	430.5	9.4	40.64	974.6	986.1	28.22	55.08	2.00	10234.0	1.22	0.83	57
26	102.40	58.2	471.8	8.5	39.89	1063.7	1092.2	71.46			7951.0	0.85		
27	101.95	55.3	439.6	9.9	43.55	985.2	1013.7	65.56			3802.0	0.43		
28	102.15	58.9	476.7	8.6	41.08	1081.4	1106.6	61.51	62.94	4.00	9345.0	0.99	0.74	51
29	102.35	55.1	458.7	8.5	39.13	1036.2	1053.8	45.10			7536.0	0.85		
30	102.70	59.8	474.6	8.8	41.54	1066.4	1100.5	82.21			3622.0	0.38		
31	102.20	62.2	504.0	9.2	46.61	1143.2	1169.9	57.34	72.16	16.00	9220.0	0.92	0.62	42
32	102.00	209.1	475.4	6.2	29.62	1074.8	1102.5	93.27			5891.0	0.18		
33	102.30	60.9	500.9	7.0	35.04	1134.1	1157.2	65.87			7378.0	0.75		
35	103.25	60.2	494.9	8.0	39.46	1126.4	1153.8	69.41	62.13	24.00	8108.0	0.83	0.86	103
36	102.45	52.6	422.9	9.0	38.23	968.1	989.1	54.85			4674.0	0.55		
37	102.40	57.0	482.4	10.2	48.99	1101.3	1123.5	45.38			10900.0	1.19		
38	102.25	60.3	488.3	8.4	40.88	1100.9	1139.3	94.13	71.53	48.00	4512.0	0.47	0.61	42
39	102.25	46.7	374.5	9.5	35.42	851.9	869.2	48.93			5011.0	0.67		
40	102.20	53.7	448.7	6.9	30.93	1005.1	1015.0	32.01			6002.0	0.70		

APPENDIX 5

T-Test Analysis of Effect of Surface Cracks on ITS

Group Statistics

	Parallel	N	Mean	Std. Deviation	Std. Error Mean
ITS	Parallel	3	.947200	.0581155	.0335530
	Perpendicular	3	.988667	.0503643	.0290778

Independent Samples Test

Equal variances assumed

Levene's Test for Equality of Variances		t-test for Equality of Means							
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
ITS	.161	.709	-.934	4	.403	-.041467	.0443996	-.1647397	.0818064

Group Statistics

	Parallel	N	Mean	Std. Deviation	Std. Error Mean
ITS	Parallel	3	.624867	.0585479	.0338026
	Perpendicular	3	.697233	.0464209	.0268011

Independent Samples Test

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means		Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
	F	Sig.	t	df				Lower	Upper
ITS	.408	.558	-1.678	4	.169	-.072367	.0431384	-.1921380	.0474046

Group Statistics

	Parallel	N	Mean	Std. Deviation	Std. Error Mean
ITS	Parallel	3	.660467	.0445226	.0257051
	Perpendicular	3	.712267	.0247496	.0142892

Independent Samples Test

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means		Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
	F	Sig.	t	df				Lower	Upper
ITS	.964	.382	-1.761	4	.153	-.051800	.0294098	-.1334547	.0298547

Group Statistics

	Parallel	N	Mean	Std. Deviation	Std. Error Mean
ITS	Parallel	3	.322900	.0674865	.0389634
	Perpendicular	3	.445467	.0875469	.0505452

Independent Samples Test

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means		Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
	F	Sig.	t	df				Lower	Upper
ITS	.163	.707	-1.921	4	.127	-.122567	.0638198	-.2997588	.0546255

Group Statistics

	Parallel	N	Mean	Std. Deviation	Std. Error Mean
ITS	Parallel	3	.947200	.0581155	.0335530
	Perpendicular	3	.660467	.0445226	.0257051

Independent Samples Test

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means		Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
	F	Sig.	t	df				Lower	Upper
ITS	.573	.491	6.784	4	.002	.286733	.0422677	.1693794	.4040873

Group Statistics

	Parallel	N	Mean	Std. Deviation	Std. Error Mean
ITS	Parallel	3	.988667	.0503643	.0290778
	Perpendicular	3	.712267	.0247496	.0142892

Independent Samples Test

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means		Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
	F	Sig.	t	df				Lower	Upper
ITS	2.733	.174	8.531	4	.001	.276400	.0323991	.1864457	.3663543

Group Statistics

	Parallel	N	Mean	Std. Deviation	Std. Error Mean
ITS	Parallel	3	.624867	.0585479	.0338026
	Perpendicular	3	.322900	.0674865	.0389634

Independent Samples Test

Equal variances assumed

Levene's Test for Equality of Variances		t-test for Equality of Means							
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
ITS	1.160	.342	4.401	4	.012	.251767	.0572112	.0929229	.4106104

Group Statistics

	Parallel	N	Mean	Std. Deviation	Std. Error Mean
ITS	Parallel	3	1.108967	.1097476	.0633628
	Perpendicular	3	.947200	.0581155	.0335530

Independent Samples Test

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means		Sig. (2- tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
	F	Sig.	t	df				Lower	Upper
ITS	3.687	.127	1.726	4	.160	.120300	.0697163	-.0732636	.3138636

Group Statistics

	Parallel	N	Mean	Std. Deviation	Std. Error Mean
ITS	Parallel	3	.854733	.0284613	.0164321
	Perpendicular	3	.660467	.0445226	.0257051

Independent Samples Test

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means		Sig. (2- tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
	F	Sig.	t	df				Lower	Upper
ITS	.161	.708	6.542	4	.003	.142467	.0217760	.0820067	.2029266

Group Statistics

	Parallel	N	Mean	Std. Deviation	Std. Error Mean
ITS	Parallel	3	.816333	.0187276	.0108124
	Perpendicular	3	.624867	.0585479	.0338026

Independent Samples Test

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means					95% Confidence Interval of the Difference	
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
ITS	5.112	.087	5.395	4	.006	.191467	.0354898	.0929312	.2900021

Group Statistics

	Parallel	N	Mean	Std. Deviation	Std. Error Mean
ITS	Parallel	3	.816333	.0187276	.0108124
	Perpendicular	3	.697233	.0464209	.0268011

Independent Samples Test

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means		Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
	F	Sig.	t	df				Lower	Upper
ITS	1.495	.289	4.121	4	.015	.119100	.0289000	.0388608	.1993392

Group Statistics

	Parallel	N	Mean	Std. Deviation	Std. Error Mean
ITS	Parallel	3	.579367	.0134664	.0077748
	Perpendicular	3	.322900	.0674865	.0389634

Independent Samples Test

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means		Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
	F	Sig.	t	df				Lower	Upper
ITS	7.542	.052	6.455	4	.003	.256467	.0397315	.1461544	.3667790

T-Test- Selecting the Suitable Test method for the Mechanical Properties

Group Statistics

	VAR00003	N	Mean	Std. Deviation	Std. Error Mean
ITSMIX1F	.00	3	.6567	.03055	.01764
	2.00	3	.3333	.04163	.02404
ITSMIX2F	.00	3	.2667	.23180	.13383
	2.00	3	.2000	.17578	.10149
ITSMIX6L	.00	3	.8467	.16803	.09701
	2.00	3	.5100	.11533	.06658
ITSMIX7L	.00	3	1.4533	.11676	.06741
	2.00	3	.8333	.39526	.22821

Independent Samples Test

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means		Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
	F	Sig.	t	df				Lower	Upper
ITSMIX1F	.500	.519	10.845	4	.000	.3233	.02981	.24056	.40611
ITSMIX2F	.561	.495	.397	4	.712	.0667	.16796	-.39967	.53300
ITSMIX6L	.561	.495	2.861	4	.046	.3367	.11766	.00998	.66335
ITSMIX7L	2.012	.229	2.606	4	.060	.6200	.23795	-.04067	1.28067

Group Statistics

	VAR00003	N	Mean	Std. Deviation	Std. Error Mean
ITSMIX1F	.00	3	.6567	.03055	.01764
	4.00	3	.3133	.02887	.01667
ITSMIX2F	.00	3	.2667	.23180	.13383
	4.00	3	.3067	.04041	.02333
ITSMIX6L	.00	3	.8467	.16803	.09701
	4.00	3	.7800	.06245	.03606
ITSMIX7L	.00	3	1.4533	.11676	.06741
	4.00	3	.7400	.31953	.18448

Independent Samples Test

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means		Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
	F	Sig.	t	df				Lower	Upper
ITSMIX1F	.000	1.000	14.148	4	.000	.3433	.02427	.27596	.41071
ITSMIX2F	9.915	.035	-.294	4	.783	-.0400	.13585	-.41718	.33718
ITSMIX6L	2.651	.179	.644	4	.555	.0667	.10349	-.22068	.35401
ITSMIX7L	3.895	.120	3.632	4	.022	.7133	.19641	.16801	1.25866

Group Statistics

	VAR00003	N	Mean	Std. Deviation	Std. Error Mean
ITSMIX1F	.00	3	.6567	.03055	.01764
	16.00	3	.4767	.04163	.02404
ITSMIX2F	.00	3	.2667	.23180	.13383
	16.00	3	.2767	.24007	.13860
ITSMIX6L	.00	3	.8467	.16803	.09701
	16.00	3	.7533	.10599	.06119
ITSMIX7L	.00	3	1.4533	.11676	.06741
	16.00	3	.6167	.38760	.22378

Independent Samples Test

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means		Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
	F	Sig.	t	df				Lower	Upper
ITSMIX1F	.500	.519	6.037	4	.004	.1800	.02981	.09722	.26278
ITSMIX2F	.010	.924	-.052	4	.961	-.0100	.19267	-.54494	.52494
ITSMIX6L	.769	.430	.814	4	.461	.0933	.11470	-.22512	.41179
ITSMIX7L	4.918	.091	3.580	4	.023	.8367	.23371	.18777	1.48556

Group Statistics

	VAR00003	N	Mean	Std. Deviation	Std. Error Mean
ITSMIX1F	.00	3	.6567	.03055	.01764
	24.00	3	.4733	.01528	.00882
ITSMIX2F	.00	3	.2667	.23180	.13383
	24.00	0	.	.	.
ITSMIX6L	.00	3	.8467	.16803	.09701
	24.00	3	.6900	.21794	.12583
ITSMIX7L	.00	3	1.4533	.11676	.06741
	24.00	3	.8567	.32083	.18523

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means		Sig. (2- tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
	F	Sig.	t	df				Lower	Upper
ITSMIX1F	1.538	.283	9.297	4	.001	.1833	.01972	.12858	.23809
ITSMIX6L	.508	.515	.986	4	.380	.1567	.15889	-.28447	.59780
ITSMIX7L	1.791	.252	3.027	4	.039	.5967	.19712	.04938	1.14395

T-Test- Phase-3**Independent Samples Test-mix1**

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
ITS	.093	.776	6.494	4	.003	.26333	.040552	.150744	.375923
MR	8.102	.065	.625	3	.577	.1517	.24285	-.62120	.92453
MS	2.761	.172	8.708	4	.016	1.6367	.95834	-1.02411	4.29744
CS	4.830	.093	12.410	4	.000	.5100	.04110	.39590	.62410

Independent Samples Test-mix-4

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
ITS	5.245	.084	2.048	4	.110	.70667	.345125	-.251553	1.664887
MR	1.328	.313	2.455	4	.070	.2533	.10317	-.03312	.53978
MS	6.664	.061	14.418	4	.000	5.2533	.36436	4.24172	6.26495
CS	4.474	.102	8.443	4	.001	.4867	.05764	.32664	.64670
SS	.036	.859	1.655	4	.173	.3200	.19330	-.21670	.85670
SM	.156	.713	3.796	4	.019	5.5200	1.45400	1.48304	9.55696

Independent Samples Test-mix5

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
ITS	1.362	.308	30.026	4	.000	.48000	.015986	.435615	.524385
MR	.246	.646	.908	4	.415	.0600	.06608	-.12347	.24347
MS	1.667	.266	7.389	4	.002	3.0733	.41595	1.91848	4.22818
CS	.400	.561	11.232	4	.000	.2900	.02582	.21831	.36169
SS	.163	.707	4.400	4	.012	.6400	.14545	.23617	1.04383
SM	1.059	.362	1.780	4	.150	3.5833	2.01304	-2.00575	9.17242

T-Test

Independent Samples Test-mix6

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
ITS	3.158	.174	5.160	3	.014	.28000	.054263	.107312	.452688
MR	2.315	.225	.133	3	.902	.0217	.16238	-.49508	.53842
MS	.056	.824	5.454	4	.028	2.4000	1.94602	-3.00301	7.80301
CS	.757	.448	8.390	3	.004	.4567	.05443	.28344	.62990
SS	.208	.672	.950	4	.396	.0900	.09469	-.17291	.35291
SM	2.239	.209	.809	4	.464	.6000	.74193	-1.45994	2.65994

T-Test

Independent Samples Test-Mix7

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
ITS	.074	.799	3.214	4	.032	.16667	.051854	.022696	.310638
MR	5.829	.095	.601	3	.590	.1533	.25499	-.65815	.96482
MS	3.069	.155	-.045	4	.966	-.0400	.89123	-2.51445	2.43445
CS	1.946	.235	2.867	4	.046	.2600	.09068	.00824	.51176
SS	.	.	6.594	2	.022	.6867	.10414	.23860	1.13473
SM	.	.	2.144	2	.165	6.6367	3.09525	-6.68112	19.95446

APPENDIX 6

Non-linear Regression-AMIR Compactor

All the derivatives will be calculated numerically.

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Iteration	Residual	SS	A1	A2	A3
1	3875.010726	.500000000	.100000000	.200000000	
1.1	524.4247038	.440081517	.099535140	-1.7942383	
2	524.4247038	.440081517	.099535140	-1.7942383	
2.1	70.97272767	.380164876	.099069592	-3.7884834	
3	70.97272767	.380164876	.099069592	-3.7884834	
3.1	9.604953265	.320253744	.098602232	-5.7827530	
4	9.604953265	.320253744	.098602232	-5.7827530	
4.1	1.299829800	.260357555	.098129927	-7.7770888	
5	1.299829800	.260357555	.098129927	-7.7770888	
5.1	.1758910310	.200501963	.097644236	-9.7716049	
6	.1758910310	.200501963	.097644236	-9.7716049	
6.1	.0237962422	.140756742	.097122136	-11.766611	
7	.0237962422	.140756742	.097122136	-11.766611	
7.1	.0032175225	.081311375	.096501103	-13.762949	
8	.0032175225	.081311375	.096501103	-13.762949	
8.1	.0004343616	.022679874	.095611755	-15.762902	
9	.0004343616	.022679874	.095611755	-15.762902	
9.1	.0000583882	-.03374801	.093996877	-17.772649	
10	.0000583882	-.03374801	.093996877	-17.772649	

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10.1 .0000077583 -.08425005 .090438325 -19.808768
11 .0000077583 -.08425005 .090438325 -19.808768
11.1 .0000009991 -.11910798 .081802122 -21.914776
12 .0000009991 -.11910798 .081802122 -21.914776
12.1 .0000001184 -.11468628 .060784186 -24.197953
13 .0000001184 -.11468628 .060784186 -24.197953
13.1 1.1472E-08 -.02418992 .014870599 -26.877569
14 1.1472E-08 -.02418992 .014870599 -26.877569
14.1 9.5029E-10 .195514165 -.05828821 -30.160296
15 9.5029E-10 .195514165 -.05828821 -30.160296
15.1 3.6584E-10 .456154646 -.11443423 -33.404578
16 3.6584E-10 .456154646 -.11443423 -33.404578
16.1 3.5393E-10 .571012445 -.12468527 -34.917008
17 3.5393E-10 .571012445 -.12468527 -34.917008
17.1 3.5387E-10 .582444328 -.12477401 -35.079103
18 3.5387E-10 .582444328 -.12477401 -35.079103
18.1 3.5387E-10 .582538780 -.12477331 -35.080463
19 3.5387E-10 .582538780 -.12477331 -35.080463

```

Run stopped after 37 model evaluations and 19 derivative evaluations.

Iterations have been stopped because the magnitude of the largest correlation
between the residuals and any derivative column is at most $RCON = 1.000E-08$

—

Nonlinear Regression Summary Statistics Dependent Variable K

Source	DF	Sum of Squares	Mean Square
Regression	3	1.050510E-08	3.501701E-09
Residual	6	3.538667E-10	5.897778E-11
Uncorrected Total	9	1.085897E-08	

(Corrected Total) 8 2.571902E-09

R squared = 1 - Residual SS / Corrected SS = .86241

Asymptotic 95 %**Asymptotic Confidence Interval**

Parameter	Estimate	Std. Error	Lower	Upper
A1	.582538780	.375576237	-.336463166	1.501540725
A2	-.124773307	.118519601	-.414780324	.165233711
A3	-35.08046293	5.373145826	-48.22807713	-21.93284873

Asymptotic Correlation Matrix of the Parameter Estimates

	A1	A2	A3
A1	1.0000	-.1603	-.9335
A2	-.1603	1.0000	-.2022
A3	-.9335	-.2022	1.0000

Non-linear Regression

All the derivatives will be calculated numerically.

Iteration	Residual	SS	A1	A2
1	.0000129357	.8000000000	-30.000000	
1.1	.0000016817	.739429300	-31.913916	
2	.0000016817	.739429300	-31.913916	
2.1	.0000002042	.678379838	-33.691454	
3	.0000002042	.678379838	-33.691454	
3.1	2.0803E-08	.617049286	-35.146844	
4	2.0803E-08	.617049286	-35.146844	
4.1	1.6162E-09	.559711617	-35.995455	
5	1.6162E-09	.559711617	-35.995455	
5.1	4.3658E-10	.521934894	-36.180434	
6	4.3658E-10	.521934894	-36.180434	
6.1	4.2035E-10	.512538840	-36.155221	
7	4.2035E-10	.512538840	-36.155221	
7.1	4.2035E-10	.512150929	-36.151824	
8	4.2035E-10	.512150929	-36.151824	
8.1	4.2035E-10	.512145786	-36.151751	

Run stopped after 16 model evaluations and 8 derivative evaluations.

Iterations have been stopped because the relative reduction between successive residual sums of squares is at most $SSCON = 1.000E-08$

Nonlinear Regression Summary Statistics Dependent Variable K

Source	DF	Sum of Squares	Mean Square
Regression	2	1.043862E-08	5.219312E-09
Residual	7	4.203469E-10	6.004956E-11
Uncorrected Total	9	1.085897E-08	

(Corrected Total)	8	2.571902E-09
-------------------	---	--------------

R squared = 1 - Residual SS / Corrected SS = .83656

Asymptotic 95 %

Asymptotic Confidence Interval

Parameter	Estimate	Std. Error	Lower	Upper
A1	.512145786	.379338015	-.384846084	1.409137656
A2	-36.15175149	5.384355474	-48.88372902	-23.41977396

Asymptotic Correlation Matrix of the Parameter Estimates

	A1	A2
A1	1.0000	-.9992
A2	-.9992	1.0000

Regression

Variables Entered/Removed

b

Model	Variables Entered	Variables Removed	Method
1	MSR ^a	.	Enter

a. All requested variables entered.

b. Dependent Variable: K

Model Summary^b

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.594 ^a	.352	.288	1.40148

a. Predictors: (Constant), MSR

b. Dependent Variable: K

ANOVA^b

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	10.689	1	10.689	5.442	.042 ^a
	Residual	19.641	10	1.964		
	Total	30.331	11			

a. Predictors: (Constant), MSR

b. Dependent Variable: K

Coefficients^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	12.490	4.595		2.718	.022
	MSR	-.125	.054	-.594	-2.333	.042

a. Dependent Variable: K

Residuals Statistics^a

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	.3363	3.3903	1.8112	.98578	12
Residual	-2.3356	2.7797	.0000	1.33626	12
Std. Predicted Value	-1.496	1.602	.000	1.000	12
Std. Residual	-1.667	1.983	.000	.953	12

a. Dependent Variable: K

Charts

APPENDIX 7

Sept 9, 2004

Mix Type	S#	Level of Compaction	D1	D2	Dav	H1	H2	Hav	WD1	WW	WD2	VOLUME	BULK DENSITY	MAX SG	% A V
			mm	mm	mm	mm	mm	mm	mm	mm	mm	cc	gm/cc	gm/cc	
4	1	1	96.1	96.7	96.4	70.5	72.2	71.4	872.65	456.08	908.38	452.3	1.93	2.44	20.9
4	2	1	97.1	96.2	96.7	69.6	68.0	68.8	885.27	464.33	920.94	456.6	1.94	2.44	20.5
4	3	1	96.4	97.2	96.8	72.1	74.0	73.1	934.22	488.04	966.40	478.4	1.95	2.44	20.0
4	4	1	96.9	97.1	97.0	72.0	72.4	72.2	945.68	493.23	972.76	479.5	1.97	2.44	19.2
4	5	1	96.7	96.3	96.5	72.4	72.2	72.3	930.17	494.23	965.73	471.5	1.97	2.44	19.1
4	6	1	96.1	96.5	96.3	74.8	71.9	73.4	956.22	499.33	985.74	486.4	1.97	2.44	19.4
4	7	1	96.3	96.6	96.5	73.1	72.8	73.0	931.52	492.15	963.55	471.4	1.98	2.44	19.0
4	8	1	96.5	96.5	96.5	73.1	73.3	73.2	921.01	487.95	955.91	468.0	1.97	2.44	19.3
4	1	2	96.7	96.5	96.6	74.8	75.2	75.0	1147.29	621.26	1153.42	532.2	2.16	2.44	11.6
4	2	2	96.3	97.5	96.9	76.1	75.7	75.9	1161.49	630.88	1164.40	533.5	2.18	2.44	10.8
4	3	2	96.3	96.3	96.3	77.2	76.2	76.7	1158.97	629.23	1165.54	536.3	2.16	2.44	11.4
4	4	2	96.6	96.4	96.5	74.8	74.3	74.6	1159.65	630.49	1164.27	533.8	2.17	2.44	11.0
4	5	2	97.1	96.7	96.9	76.4	76.4	76.4	1168.07	636.04	1173.17	537.1	2.17	2.44	10.9
4	6	2	96.4	97.3	96.9	74.2	74.9	74.6	1105.21	593.67	1111.65	518.0	2.13	2.44	12.6
4	7	2	96.4	96.3	96.4	73.6	75.3	74.5	1101.61	592.20	1110.93	518.7	2.12	2.44	13.0
4	8	2	96.8	96.1	96.5	75.4	74.8	75.1	1106.66	595.26	1118.12	522.9	2.12	2.44	13.3
4	1	3	96.3	97.0	96.7	64.9	65.9	65.4	1036.39	574.30	1037.96	463.7	2.24	2.44	8.4
4	2	3	96.3	96.9	96.6	65.0	66.2	65.6	1036.47	576.78	1038.10	461.3	2.25	2.44	7.9
4	3	3	96.2	96.9	96.6	65.4	64.5	65.0	1022.01	568.63	1024.48	455.9	2.24	2.44	8.1
4	4	3	96.6	96.4	96.5	63.4	65.4	64.4	1027.07	568.30	1028.97	460.7	2.23	2.44	8.6
4	5	3	96.6	97.1	96.9	65.9	66.2	66.1	1033.76	571.64	1037.58	465.9	2.22	2.44	9.1
4	6	3	97.8	96.3	97.1	65.5	66.2	65.9	1049.59	584.02	1051.21	467.2	2.25	2.44	7.9
4	7	3	96.9	96.5	96.7	62.9	63.0	63.0	1003.62	559.41	1005.14	445.7	2.25	2.44	7.7
4	8	3	96.4	96.4	96.4	61.6	61.9	61.8	987.69	547.91	989.97	442.1	2.23	2.44	8.4

Sept 9, 2004		Level of Compaction		D1		D2		Dav		H1		H2		Hav		WD1		WW		WD2		VOLUME		BULK DENSITY		MAX SG		% A V	
Mix Type	S#			mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	cc	cc	gn/cc	gn/cc	gn/cc	gn/cc		
5	1	1		98.3	98.5	98.4	98.3	98.4	98.3	98.4	98.3	98.4	98.3	98.4	98.3	98.4	98.3	98.4	98.3	98.4	98.3	485.4	485.4	2.01	2.44	2.44	17.6		
5	2	1		98.0	98.6	98.3	98.3	98.3	98.3	98.3	98.3	98.3	98.3	98.3	98.3	98.3	98.3	98.3	98.3	98.3	98.3	497.0	497.0	1.97	2.44	2.44	19.3		
5	3	1		96.6	96.4	96.5	96.3	96.5	96.3	96.5	96.3	96.5	96.3	96.5	96.3	96.5	96.3	96.5	96.3	96.5	96.3	468.9	468.9	2.00	2.44	2.44	18.2		
5	4	1		96.2	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	468.8	468.8	1.97	2.44	2.44	19.4		
5	5	1		96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	483.3	483.3	1.97	2.44	2.44	19.4		
5	6	1		97.5	96.1	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	482.8	482.8	2.00	2.44	2.44	18.2		
5	7	1		96.2	96.4	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	480.6	480.6	1.98	2.44	2.44	19.0		
5	8	1		96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	477.5	477.5	1.99	2.44	2.44	18.3		
5	1	2		96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	520.5	520.5	2.19	2.44	2.44	10.4		
5	2	2		96.3	96.0	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	527.1	527.1	2.17	2.44	2.44	11.2		
5	3	2		96.7	97.2	97.0	97.0	97.0	97.0	97.0	97.0	97.0	97.0	97.0	97.0	97.0	97.0	97.0	97.0	97.0	97.0	514.9	514.9	2.19	2.44	2.44	10.3		
5	4	2		96.4	96.1	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	526.2	526.2	2.20	2.44	2.44	9.8		
5	5	2		96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	528.0	528.0	2.19	2.44	2.44	10.2		
5	6	2		96.8	96.7	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	517.3	517.3	2.18	2.44	2.44	10.6		
5	7	2		96.2	96.5	96.4	96.4	96.4	96.4	96.4	96.4	96.4	96.4	96.4	96.4	96.4	96.4	96.4	96.4	96.4	96.4	524.5	524.5	2.18	2.44	2.44	10.5		
5	8	2		96.3	95.7	96.0	96.0	96.0	96.0	96.0	96.0	96.0	96.0	96.0	96.0	96.0	96.0	96.0	96.0	96.0	96.0	530.1	530.1	2.17	2.44	2.44	11.0		
5	9	2		96.2	96.4	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	526.0	526.0	2.16	2.44	2.44	11.3		
5	1	3		96.2	96.1	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	506.1	506.1	2.23	2.44	2.44	8.8		
5	2	3		96.1	96.5	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	501.5	501.5	2.22	2.44	2.44	8.9		
5	3	3		96.1	96.7	96.4	96.4	96.4	96.4	96.4	96.4	96.4	96.4	96.4	96.4	96.4	96.4	96.4	96.4	96.4	96.4	525.2	525.2	2.24	2.44	2.44	8.1		
5	4	3		96.0	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	530.1	530.1	2.22	2.44	2.44	9.0		
5	5	3		96.1	96.3	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	535.1	535.1	2.24	2.44	2.44	8.1		
5	6	3		96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	532.0	532.0	2.24	2.44	2.44	8.2		
5	7	3		96.3	96.1	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	96.2	533.1	533.1	2.21	2.44	2.44	9.5		
5	8	3		96.4	96.2	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	532.8	532.8	2.23	2.44	2.44	8.6		
5	9	3		96.4	96.2	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	96.3	537.0	537.0	2.24	2.44	2.44	8.1		

TENSILE STRENGTH RATIO					MIX TYPE		4		
					Level of compaction:		1		
					Dry		Wet		
SAMPLE		1	2	3	4	5	6	7	8
AVERAGE AIR VOIDS									
STABILITY		12832		15265	17734	0	0	0	0
CORRECTION FACTOR		0.83		0.81	0.83				
CORRECTED STABILITY		10650.56		12364.65	14719.22				
AVERAGE STABILITY		12578.1				0.0			
RETAINED STABILITY		Failed During Conditioning							

TENSILE STRENGTH RATIO				MIX TYPE		4			
				Level of compaction:		2			
				Dry			Wet		
SAMPLE		1	2	3	4	5	6		
AVERAGE AIR VOIDS									
STABILITY		39136	42213	39761	26268	24156	24986		
CORRECTION FACTOR		0.78	0.78	0.76	0.78	0.78	0.78		
CORRECTED STABILITY		30526.08	32081.88	30218.36	20489.04	18841.68	19489.08		
AVERAGE STABILITY		30942.1			19606.6				
RETAINED STABILITY		63.4							

TENSILE STRENGTH RATIO				MIX TYPE		4			
				Level of compaction:		3			
				Dry			Wet		
SAMPLE				1	2	3	4	5	6
AVERAGE AIR VOIDS									
STABILITY				45453	41608	43984	34472	30478	30128
CORRECTION FACTOR				0.96	0.96	0.96	0.93	0.96	1.00
CORRECTED STABILITY				43634.88	39943.68	42224.64	32058.96	29258.88	30128.00
AVERAGE STABILITY				41934.4			30481.9		
RETAINED STABILITY				72.7					

TENSILE STRENGTH RATIO				MIX TYPE				5			
				Level of compaction:				1			
				Dry				Wet			
SAMPLE		1	2	3	4	5	6	7	8		
AVERAGE AIR VOIDS											
STABILITY		17852	19590	18590	16844	13123					
CORRECTION FACTOR		0.81	0.83	0.81	0.81	0.81	0.81	0.81	0.81		
CORRECTD STABILITY		14460.12	16259.70	15057.90	13643.64	10629.63	10055.34	10162.26	9819.63		
AVERAGE STABILITY		14855.3				10166.7					
RETAINED STABILITY		68.4									

TENSILE STRENGTH RATIO				MIX TYPE				5			
				Level of compaction:				1			
				Dry				Wet			
SAMPLE		1	2	3	4	5	6	7	8		
AVERAGE AIR VOIDS											
STABILITY		38505	38744	42643	25300	29635	28919	29610	29244		
CORRECTION FACTOR		0.81	0.78	0.81	0.78	0.78	0.81	0.78	0.78		
CORRECTD STABILITY		31189.05	30220.32	34540.83	19734.00	23115.30	23424.39	23095.80	22810.32		
AVERAGE STABILITY		28921.1				23111.5					
RETAINED STABILITY		79.9									

TENSILE STRENGTH RATIO				MIX TYPE				5			
				Level of compaction:				1			
				Dry				Wet			
SAMPLE		1	2	3	4	5	6	7	8		
AVERAGE AIR VOIDS											
STABILITY		44496	40619	48094	47668	39671	39972	39027	41403		
CORRECTION FACTOR		0.83	0.83	0.78	0.78	0.83	0.83	0.79	0.78		
CORRECTD STABILITY		36931.68	33713.77	37513.32	37181.04	32926.93	33176.76	30831.33	32294.34		
AVERAGE STABILITY		36335.0				32307.3					
RETAINED STABILITY		88.9									

Correlation Between Permeability and Marshall Stability Ratio

Correlations

		K	MSR
K	Pearson Correlation	1	-.594*
	Sig. (2-tailed)	.	.042
	N	12	12
MSR	Pearson Correlation	-.594*	1
	Sig. (2-tailed)	.042	.
	N	12	12

*. Correlation is significant at the 0.05 level (2-tailed).