Quality Control of Asphalt Pavement Field Compaction Using Field-Measured Pavement Permeability

by

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Abstract

For decades, the use of rotary steel drum compaction train to compact asphalt concrete and the use of density as a quality control criterion for job acceptance have been the mainstream practices. These have remained essentially unchanged since their respective adoptions by the industry. Hence, asphalt material properties have been overemphasized with no consideration of the impact of construction processes. Limiting the intrusion of water into the body of asphalt concrete pavement has been an age-long recommendation. This was found to reduce the potential of asphalt concrete moisture damage susceptibilities. However, attempts to reliably measure asphalt pavement permeability in the field or correlate it to other surrogates have been unsuccessful or at least unreliable, thus, frustrating the applicability of permeability measurements.

This thesis seeks to solve the aforementioned problems by measuring asphalt pavement permeability in the field and relating the measured permeability coefficients to different construction factors. The study also compares the rotary steel drum compaction technologies and the AMIR to highlight the effects of different compaction methods on the properties of asphalt pavements with a focus on permeability as an alternative quality control property. Ten sites were selected for the field compaction used in this thesis to study the effects of different field compactors on asphalt pavement compaction and permeability. Case one of the field compaction studies involved the use of vibratory train and AMIR in nine projects. Case two involved the use of the vibratory and oscillatory trains and AMIR compactors in one project.

The results of field compaction and permeability using the rollers indicate that AMIR compactor yields asphalt pavement surfaces with lower permeability at a

comparable level of compaction with the vibratory or oscillatory train compaction methods. AMIR compactor was also found to reduce the mean permeability of the surfaces compacted on concrete base compared to the conventional rotary steel drum compactors and was also more efficient. Also, this thesis further presents new developments in field measurements of permeability. Based on laboratory trials and calibrations that employ the electronic water level sensor system, a new device termed “Carleton Permeability Device” is developed and proposed.

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Dedication

To the legacies and blessed memories of Late Professor Abd El Halim Omar Abd El Halim.

To H.E. Martin Nwancho Elechi, MFR for his visionary and humane leadership.

To my parents, and siblings for their financial contributions and all-round support.

To Daberechi, Munachi and Ugochi.

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Chapter 1: Introduction

1.1 Background

The design of asphalt road pavements incorporates factors such as traffic (based on axle loadings, configurations, and projected traffic growths), climatic conditions, drainage considerations, and performance indicators. These design factors dictate the structural provisions for the new pavement to be constructed. Usually, service life ranging from 15 to 25 years is projected. However, this fundamental target is hardly met owing to some mismatch or discrepancies in laboratory design controls and field implementation factors. For instance, while the hot mix asphalt (HMA) is confined in most laboratory compaction with minimal heat loss, compacted with a ram or a hammer as the case may be; field compaction occurs in an open field, unconfined, and with substantial heat losses. Furthermore, the actual effects of climatic and other environmental degradation factors that the asphalt pavement would be subjected to throughout its service life are not properly accounted for in the laboratory environment. These discrepancies and their effects contribute to the early manifestation of various kinds of distresses on the asphalt roads; some as early as a couple of weeks after construction (Abd El Halim and Abdelzaher, 2006; Awadalla, et al., 2017; Rollings and Rollings, 1992; Williams, 2015).

Although different mix design practices have evolved over the past decades, with the Superpave system being the latest in North America; the fundamental problem of long-term performance of the asphalt concrete roads remains an industry challenge. While this is the case, the field compaction equipment has remained essentially unchanged for over 140 years since the first steam roller was invented (i.e. the use of rotary steel drum

compactor). Furthermore, the density of the compacted pavement is used as a sole quality control property in quality control and job acceptance by most highway agencies worldwide (Geller, 1984; Hughes, 1989; Parker, 1960).

Asphalt pavement compaction is the dominant and controlling factor that affects the final pavement properties controlling for other factors such as mix design, environmental factors, etc. Research findings from the early 1980s have shown that asphalt pavement early distress manifestations have more to do with the process and equipment of field compaction used during construction, than the mix design properties. However, this observation has not received due attention and considerations amongst the highway/paving practitioners. Miller (2010) concluded that the current literature is mainly concerned about the characteristics and properties of asphalt concrete from a material perspective and that little attention had been given to the effects of the construction process on the quality of asphalt pavement. While present compaction equipment may achieve recommended density, other desirable pavement properties such as strength, acceptable impermeability level, surface characteristics, resistance to damages and distresses may be impaired (Abd El Halim and Abdelzaher, 2006; Darban, 1993; Abd El Halim et al., 1994; Kearney, 2006).

Permeability (usually of water) is the fundamental property of porous media such as asphalt concrete to admit and pass (conduct) water. Asphalt pavement permeability determines the extent and magnitude of the intrusion of moisture and other potentially deleterious substances into the body of the mix or pavement. The importance of permeability on the performance and durability of asphalt pavement has been recognised and researched since the 1940s. Numerous research investigations have recommended the incorporation of asphalt pavement permeability into the quality control protocols (Harris,

2007; Kandhal and Mallick, 2007; Mallick and Daniel, 2006; Mallick et al., 2003; Williams, 2011; Hveem, 1940). Strangely, this recommendation has not been fully taken into consideration or sufficiently implemented till now. This is because of limitations in conception, field applications and standardization of asphalt pavement field permeability measurements. If permeability is to be incorporated into the quality control scheme of asphalt pavements; it is, therefore, essential to know the inherent field factors that affect asphalt pavement permeability especially during construction, as well as to accurately and efficiently measure it in the field.

1.2 Problem Definition

Key performance attributes or properties of asphalt concrete pavements that are controlled by compaction include strength, resistance to ageing or durability, moisture damage resistance, and impermeability, and there are strong links between these three properties (Finn and Epps, 1980; Hughes, 1989). A plethora of findings in the literature suggests that permeability affects moisture susceptibility, ageing, and durability of asphalt concrete pavement. Tarefder and Ahmad (2015) evaluated the relationship between the permeability and moisture damage of pavements and concluded that moisture damage is related to permeability. They also found that the well-performing pavements have lower permeability values compared to the ones not performing well. Caro et al. (2008a) and Kassem (2008) suggested that permeability is one of the major pavement properties which controls the moisture transport within asphalt pavement and the extent of moisture damage. Early engineers recognised the importance of maintaining a balance between stability and durability, water tightness and vapour porousness (McKesson, 1949; Zube, 1962). The extent of oxidative and ultraviolet ageing is strongly related to the ease by which the

detrimental fluids and elements are conducted through the body of asphalt concrete which is influenced by permeability (Das et al., 2015; Igboke et al., 2018).

Asphalt pavement quality control specifications have changed from “method based” to “end-result based”, and in some cases, incorporating statistical limits in quality control values (Geller, 1984; Hughes, 1989). Currently, most highway jurisdictions use relative compaction as a sole quality control indicator for the job acceptance and payment of the contractors. Research findings suggest that while conventional field compactors that utilize rotary steel drums are able to achieve the desired density levels; they, however, produce pavements that are highly permeable with lower performance indicators as well as poor surface characteristics (Abd El Halim and Abdelzaher, 2006; Abd El Halim et al., 2009; Igboke et al., 2018; Omar et al., 2018). Furthermore, while less permeable asphalt concrete pavement may be related to high density, and by extension, high pavement strength characteristics; high density and strength characteristics of asphalt pavement do not necessarily assure low-permeability and durable asphalt concrete pavements. These are supported by the findings of researchers such as Bhattacharjee & Mallick, (2002); Kandhal and Mallick, (2007); Mallick & Daniel, (2006); Mallick et al., (2001) and Williams, (2011) to mention just a few.

From these foregoing findings, one would question the rationale behind the continued use of density as a sole quality control criterion even when it has been proven that different mixes have different permeability values at the same compaction levels (Mallick, 2007; Mallick & Daniel, 2006). The implications are that mixes of different gradations would have acceptable density and satisfy most agencies’ acceptance criteria. However, they would have different permeability values and by extension different

durability and moisture damage susceptibilities. Hence, authors such as Cooley and Brown (2000); Fleckenstein et al. (2002); Hveem et al. (1959); Kandhal and Mallick (2007); Mallick and Daniel (2006); Ekse (1953); McKesson (1949); McLaughlin & Goetz (1955) and Williams (2011) have proposed that the better correlate or surrogate to pavement performance and durability is permeability.

Consequently, efforts and research have been geared towards measuring permeability both in the laboratory and in the field. One main problem is that most of the work on asphalt pavement permeability has to do with research rather than the much-needed field applications and implementations. A good number of permeameters have been developed and used to quantify asphalt concrete permeability in the field, and the laboratory. Some of the permeameters use air as the conducted fluid while others employ water. Furthermore, pressure head driving the flow could be based on the falling head or constant head principles (Brown et al., 2004; Choubane et al., 1998; Cooley and Brown, 2000; Hall, 2004).

Among these permeameters, NCAT (National Centre for Asphalt Technology) permeameter seems to be most popular owing to its simple operation, and cost-effectiveness (Awadalla, 2015; Cooley and Brown, 2000). However, the design and application of different permeameters that exist in the literature are either deficient, difficult to apply or their uses are ambiguous. Many results obtained from some of the permeameters were difficult to conceptualize without correlating their results with the NCAT permeameter or void content. Also, some of the permeameters are costly; tests are not easily repeatable and hence, not efficient, or reliable. Data acquisition during testing of highly permeable pavements is extremely challenging due to the rapid drainage of water.

Laboratory permeability test of field samples which involves coring from pavement sections is very costly, time-consuming, as well as subject to the problems of changing the basic properties of the samples due to the effects of coring which contributes to pavement deterioration. Another major problem of field permeability measurement is the inability to use similar laboratory apparatus as a surrogate to estimate field permeability. Research findings on this subject are either conflicting or uncertain at best. Measuring permeability in the field, not only represents the real-life condition at the time of testing, but also represents what is in-place, and provides the contractor the timely opportunity to apply correction where needed (Russell et al., 2005; Brown et al., 2004).

Having recognized the importance of permeability measurements to the quality controls and long-term performance of asphalt concrete pavement, it is pertinent that; (a) an evaluation to aid adequate understanding of how the current field compaction equipment and other construction factors affect field permeability of asphalt concrete pavement is carried out, and (b) an efficient, robust, cost-effective, time-saving and repeatable field permeability device be developed and used in the field. This would not only save the time and resources used in destructive sample collections and testing but would also yield the needed outcomes in the field during construction, thereby giving ample time for amendment when necessary in ensuring the quality and durability of asphalt pavements.

1.3 Research Objectives and Scope

The purpose of this research is to complement and advance the previous body of knowledge in the area of asphalt pavement field compaction, water permeability and quality controls. As discussed above, and more specifically, the problems of asphalt pavements performance and durability appear to be related to construction processes and

techniques, and the lack of reliable QC/QA techniques. Based on the problem definition in Section 1.2, the following research questions are developed; what are the most important construction or paving processes that affect the performance and durability of asphalt pavements? What are the properties of the asphalt pavements that have strong links to the most important construction or paving processes and durability? Are these properties quantifiable, and can they be reliably measured in a cost-effective and timely manner? What are the current measurement methods in place for these properties? What problems are encountered in these measurements and how can they be mitigated? To provide plausible answers to these research questions, the major aims and objectives of this research are as follows:

- Identify and evaluate the effects of the compaction technologies available to the asphalt paving industry on key asphalt pavement quality control attributes related to field compaction and permeability. These are followed with the investigation and identification of the major quality control field and construction variables that affect the field permeability of asphalt pavement at the time of construction as well as establish their interrelationships.
- Research and identify a cost-effective and reliable mechanism to electronically measure water volumes and levels. Use the electronic mechanism that tracks and measures water level changes automatically to conduct testing, trials, calibrate and devise a means to consistently and reliably measure the permeability of asphalt pavements or samples. Use the electronic sensor system on the existing laboratory and field equipment to measure the permeability of asphalt concrete for refining and validating the electronic sensor system's capacity and propose a new device.

1.4 Research Plan

To achieve the objectives enumerated above, a research plan and methodology were devised. First, an extensive literature review was embarked on to understand the current state of the body of knowledge of the research topic to identify the missing gaps and to fill them. This is followed by a comprehensive field and laboratory programme. Field investigations involved collaborative and coordinated work between a provincial highway agency, the MTO (Ministry of Transportation Ontario) and a local contractor R.W. Tomlinson Ltd in some selected asphalt paving projects. The paving operation involved using the mainstream compaction technologies such as the vibratory and oscillatory steel drum compaction in comparison with the AMIR (Asphalt Multi-Integrated Roller) compactor to study the effects of different compaction technologies on the properties and performance of asphalt pavement with a focus on compaction and permeability measurements. Laboratory investigations involved taking cores from the field as well as reproducing some cores in the laboratory using field mixes to determine relevant properties and take some pertinent measurements. Results emanating from the aforementioned undertaking are presented with the hope of providing some relevant knowledge to the asphalt paving industry and stakeholders.

1.5 Organisation of the Thesis

The organisation of this work is as follows;

- Chapter one discusses the background of this work. It covers the introduction, the motivations, the research method and plan that are used in this study as well as the organization of this work.

- Chapter two contains the critical review of related literature in asphalt pavement permeability and its measurements as well as factors that affect permeability. A look at the existing methods of measuring permeability in the field was undertaken with a view to identifying gaps in the literature.
- Chapter three outlines and details the research plan and methods used in this study to achieve the stated goals and objectives.
- Chapter four presents comprehensive field measurements of permeability using the NCAT permeameter, its trend pattern and also deals with the understanding, calibration, and testing of the integrated water permeability sensor assembly, some derivations, calibrations, and philosophy underlying its use.
- Chapter five presents the comprehensive results of the different field and laboratory works conducted on the subject matter of field compaction technologies and quality control related to permeability and its measurements.
- Chapter six presents the conclusions of the main findings and makes recommendations.

1.6 Thesis Contributions

Asphalt pavement construction processes have fundamentally remained unchanged despite substantial advances and changes in material sciences, engineering as well as the associated technologies, specifications, and standards. Asphalt pavement mix designs and assessments depend heavily on laboratory formulations on whose results field performances are predicated. As highlighted in the background, the laboratory environment differs in so many ways from the field environment, but the end-result specification method fails to take this into consideration. This is particularly so in the area of asphalt pavement

field compaction in relation to its laboratory counterpart and quality control. Hence, the specific contributions of this thesis are as follows.

- (a) This thesis contributes to the literature by showing that the properties of asphalt concrete compacted by the various laboratory compaction methods differ from properties of the field compacted specimens even though they were made from the same mix and compacted at a similar temperature. Thus, the findings of this work would help highway specification and standards agencies to be cautious in the use of laboratory compaction in assessing field compacted specimens.
- (b) The primary objective or interest of supervising agencies is achieving a set minimum compaction level irrespective of the method used. Several trials in this work using the various field compaction methods would provide asphalt paving stakeholders with the necessary data and information on the inherent attributes and effects of the various field compaction methods on the properties of asphalt concrete. This will no doubt enable them to fine-tune specifications and standards to achieve desired objectives in job acceptance.
- (c) Furthermore, as more emphasis is placed on achieving compaction level, less attention is paid to the construction attributes such as the interactions between the compacted surface and the base layer on the end-result properties of asphalt concrete pavements. This thesis provides the data and information on the interactions between the compacted asphalt concrete layer and the typical base layer surfaces encountered during construction and their possible effects on the quality control properties of asphalt concrete.

- (d) Following the results of the literature search, the various data, information and findings of this research, the work makes case for the use of permeability as an alternative quality control variable to be used in assessing asphalt concrete pavements.
- (e) This work further provides data, information and develops a simple and easy-to-use methodology in using electronic water level sensor in measuring permeability coefficient values of asphalt concrete as an advancement or improvement to the current systems in use. This methodology of measurements can be adapted to any device that is based on falling head principles.
- (f) This thesis develops, field tests and proposes an integrated permeability device to be used in assessing field permeability of asphalt concrete to aid quality control of field compacted asphalt specimens.

Chapter 2: Literature Review

2.1 Introduction

Asphalt concrete is a viscoelastoplastic, heterogeneous, porous, particle composite whose properties are derived from the properties of the constituent materials and are influenced by the extent of its densification and the surrounding environment. It exhibits properties between solid and liquid phases depending on temperature and time. Furthermore, asphalt concrete is the commonly used material in road paving with about 85% to 90% of all world paved roads employing its use (Caro et al., 2010; Abd El Halim et al., 2006).

The performance and durability of asphalt concrete pavement are strongly related to compaction which in turn influences the following properties: strength, ageing, moisture damage, permeability, and skid resistance (Finn and Epps, 1980; Hughes, 1989). These properties play a major role in the performance and durability of asphalt pavements. Foremost engineers and researchers recognized the importance of maintaining relative pavement's impermeability while allowing the pavement to "breathe" i.e. vapour exchange as well as to maintain a balance between durability and stability; vapour porousness and water tightness to avoid the bleeding of asphalt pavements (Ekse and Zia, 1953; McKesson, 1949). This is because of the ease with which detrimental fluids (air and water) are conducted and transmitted through the body of asphalt concrete and their resulting effects which include oxidation, ageing, premature cracking, moisture damage and ravelling (Airey et al., 2002; Caro et al., 2008a, 2008b; Caro et al., 2010; Chen et al., 2004; Ellis & Schmidt, 1961; Standiford et al., 1985; Zube, 1962).

In a cold climate like Canada, the effects of the presence of moisture in asphalt concrete pavements and freeze-thaw action contribute to the significant number of potholes and their damaging impacts during the winter periods. In more tropical climates, seepage of moisture through the asphalt pavement layers could saturate, weaken and contribute to the sudden loss of strength of the underlain road materials and resulting in early distresses such as fatigue cracking and deformations of the pavements. Figure 2-1 shows a typical pothole in Ottawa City roads during the winter months. Very large potholes and all forms of cracks are a common sight on Ottawa City roads with heavy thuds, bent or damaged rims, collisions and other associated hazards are their common resultant effects to the riding public. As of March 21st 2019, the City of Ottawa reportedly filled over 51,000 potholes and counting for the 2018/2019 Winter season according to CTV News (2019) while over 150,000 potholes were filled in the year 2016 according to CBC News (2017).

Figure 2-1 Typical Deep Hole on Ottawa City Roads During the Winter/Spring Times (CTV News, 2019)

This chapter reviews the related literature on asphalt pavement field permeability and compaction and the works that have been done in the subject area to identify missing gaps and fill them with respect to the measurements and quantification of field permeability of asphalt pavements, their limitations in order to establish justification and build the foundation of this work. In this thesis, the term permeability and permeability coefficient may be used interchangeably.

2.2 Factors Affecting Permeability

Permeability (of a porous medium such as asphalt concrete) is a property that determines the magnitude of flow (flow rate or quantity) of a given fluid (usually water) across a given cross-sectional area or boundary. It could also be seen as a speed of flow across a porous medium. Several factors such as aggregate characteristics, binder content, maximum nominal aggregates sizes, fine aggregates content, the density of the compacted mixture have been identified to affect the permeability of asphalt concrete pavement (Abdullah et al., 1998; Choubane et al., 1998; Cooley and Brown, 2000; Cooley and Maghsoodloo, 2002; Mallick et al., 2001; Mallick et al., 2003; Washington DoT, 2005; Williams, 2009). In-situ pavement characteristics, some construction processes and equipment also affect the permeability of asphalt pavement. Variables such as layer thickness, mix segregation during placement, the temperature of the mix during breakdown rolling, temperature of the mix during pneumatic rolling, the weight of breakdown roller, tire or contact pressure of the pneumatic roller, ambient temperature during placing of the mix, void content of the compacted mix, stiffness of the underlain layers, amount and classes of traffic before winter rains affect asphalt pavement permeability. (Brown et al., 2004; Christensen and Bonaquist, 2015; Hainin et al., 2013; Russell et al., 2005;

Vardanega, 2014; Vardanega and Waters, 2011; Washington DoT, 2005; Williams, 2011; Zube, 1962). This section discusses factors that affect the permeability of asphalt concrete pavement based on previous research works with a view to understanding the current state of knowledge, identify gaps, fill the gaps and advance the state of knowledge.

2.2.1 Permeability and Pavement Thickness

Permeability of any porous medium such as asphalt concrete is a fundamental property that ideally should not depend on the physical dimensions of the measured medium. However, due to field-specific construction processes and the heterogenic/anisotropic nature of asphalt concrete; an effect is observed for field permeability relative to the laboratory permeability. Pavement lift or layer thickness, number of layers and bonding affect the permeability of the compacted mix (Allen et al., 2001; Awadalla, 2015a; Brown et al., 2004; Ellis & Schmidt, 1961; Kanitpong et al., 2001; Russell et al., 2005). Findings from field implementation of Superpave mixes by the Florida Department of Transport on I-75 highway which included mixes with different NMAS (Nominal Maximum Aggregates Sizes) and thicknesses suggest that increased thickness could lead to better density and permeability performance (Choubane et al., 1997). These findings have further suggested that thickness to NMAS ratio ($t/NMAS$) of 4.0 is preferred to optimise compaction and reduce permeability. It is usually recommended that a minimum $t/NMAS$ of 3.0 be used. This recommendation agrees with the NCAT (National Centre for Asphalt Pavement Technology) findings which showed that the lowest permeability values were also found with a ' $t/NMAS$ ' ratio of 4.0 (Mallick et al., 2003; Washington DOT, 2005).

However, Ekse and Zia (1953) suggested that increased thickness increases the pavement permeability of asphalt pavements due to the increasing number of air channels across the pavement width which also agrees with the permeability equation. Research findings by Brown et al. (2004) and Gogula et al. (2003) suggest that permeability generally decreases with increased thickness to NMA ratio with laboratory vibratory compaction technology. However, no such evidence was shown when gyratory compaction is used (Kanitpong et al., 2001; Russell et al., 2005). Furthermore, field studies by Brown et al. (2004) showed that for 9.5mm NMA fine-graded HMA (Hot Mix Asphalt); permeability increased with increased thickness for laboratory and field permeabilities, although the relationship for the laboratory permeability is weak. Also, for the 9.5mm NMA coarse-graded mix; laboratory permeability decreased with increased thickness, but field permeability increased with increased thickness when steel roller compaction was used alone without a pneumatic roller. The reverse is observed when the combination of steel and pneumatic roller is used. The same conclusion applies to the SMA (Stone Mastic Asphalt) mix employed in the study by Brown et al. (2004).

The inconclusive results of the effect of pavement layer thickness on permeability stem from two major factors; the effect of conventional compaction equipment which uses the rotary steel drum and the time available for compaction of the asphalt layer before the cessation temperature (Gogula et al., 2003; Hanain et al., 2013, Abd El Halim and Abdelzaher, 2006; Abd El Halim et al., 2013, Mohamed et al., 1993 Abd El Halim et al., 1988). The effect of temperature on the permeability of asphalt pavements arises from the fact that the pavement loses heat during compaction down to a point termed “cessation temperature” below which further compaction efforts do not significantly increase

densification (Nose 2006; Lemon 2011; Finn and Epps 1980). The use of conventional steel drum roller results in the pavement with density gradient across the pavement lift thickness with the top and bottom regions of the layer thickness having lower densities compared to the middle section of the lift which has the highest density (Nose, 2006). Furthermore, the steel drum causes surface cracks on the surface of the newly compacted asphalt concrete which impose connected air void systems that lead to higher permeability and weaker strength characteristics of the pavements especially for the thinner pavement lifts (Gogula et al., 2003; Mohammed et al., 1993; Abd El Halim et al., 1988;). Figure 2-2 shows the distribution of density across the pavement layer thickness according to Nose, (2006). Similar findings by Brown et al. (2004) showed that the effects of steel drum roller with or without combination with the rubber-tired roller are not consistent with the density as shown in Figure 2-3.

Figure 2-2 Density Gradient Effect of Steel Drum Compaction (Nose, 2006)

Figure 2-3 Effect of Roller Combinations on Asphalt Pavement Compaction (Brown et al., 2004)

Field studies by Hainin et al. (2013) indicate that increased pavement thickness could potentially reduce pavement permeability depending on the compaction and the combinations of compactors used in the field which are the field-specific effect of field compaction equipment and the compaction temperatures. Hainin et al. (2013) also concluded that pavements thickness less than or equal to 30mm with a coarse gradation have a greater chance of having a permeability problem, even though they are compacted at the right density. Furthermore, the thinner the pavement layer, the faster the mix cools, thus reducing the time available for compaction resulting in higher permeability values. Figure 2-4 shows the change of temperature (cooling) during compaction as the density evolves or grows across the pavement layer thickness with time using the various modes of the steel drum and the rubber-tired compactors where applicable while Figure 2-5 shows the cooling curves during compaction for different pavement thickness. Although looking

at Figure 2-4, density increased with an increasing number of passes of the compactor. However, it is evident that the density growth is not consistent with the number of passes of the compactor, in that decompaction could take place when compaction mode is changed or switched from one mode to the other.

Temperature and Density Data at Location t/NMAS 2.2 for Steel and 2.1 for Rubber Section

Figure 2-4 Cooling Curve, Density Evolution and Compaction Time for Different Compactors (Hainin et al., 2013)

Figure 2-5 Cooling Curve, Compaction Time and Pavement Thickness (Hainin et al., 2013)

2.2.2 Permeability and Air Voids

The most critical factor that affects the permeability of asphalt concrete is the percentage of air voids of the compacted mix (referred to simply as air voids), both for the laboratory and the field compacted mix (Brown et al., 2004). Most research findings concluded that permeability increases with air voids (Abdullah et al., 1998; Choubane et al., 1998; Chen et al., 2019; Kanitpong et al., 2001; McLaughlin and Goetz, 1955; Zube, 1962). While Cong et al. (2016); Ellis & Schmidt (1961); Mallick et al. (2001); Mallick et al. (2003); Ekse & Zia (1953); Williams (2011); Bhattacharjee et al. (2002); Cooley and Brown (2000) and Zube (1962) reported an exponential relationship between permeability and air voids; Awadalla et al. (2017); Kanitpong et al. (2001) and Yan et al. (2016) reported a power-law relationship between permeability and air voids. While reporting the

relationship of air voids and permeability, two factors should be specified and kept in mind; whether the reported permeability was a field or laboratory-measured, and whether the tested specimens were field compacted or laboratory compacted cores. Usually, the strength of the relationship between permeability and air voids varies from very strong for laboratory compacted samples to very weak for field compacted samples.

Most highway jurisdictions usually specify limits of asphalt compaction level that is acceptable to warrant payments to the contractor. In Ontario, the Ministry of Transportation Standards and Specifications OPSS 310 of November 2010 provides a minimum compaction level to be achieved for different mix designation according to Table 2-1 (MTO, 2010).

Table 2-1 OPSS 2010 Minimum Pavement Compaction for MTO (OPSS 310, pg. 21)

<i>Mix Type</i>	<i>Minimum Compaction Level (%)</i>
<i>HDBC</i>	<i>91</i>
<i>Superpave 19.0 and 25.0</i>	<i>91</i>
<i>All Others</i>	<i>92.0</i>
<i>HDBC: Heavy-Duty Binder Course</i>	

This is done in the belief that a minimum set level of compaction ensures an acceptable level of air voids that guards against excessive water permeability and ensures a durable asphalt pavement against ageing and moisture damages. However, Zube (1962) cautioned that while it is a general assumption that the permeability and durability of asphalt concrete pavement are more or less proportional to the air voids level; certain size dimensions of the individual voids and their connectivity could easily produce a pavement relatively high in air voids level but with low permeability for the compacted asphalt concrete. The most

important delimiting factor in the relationship of the air voids of the compacted asphalt mix with permeability is the connectivity or the effectiveness of the void pathways to conduct through water or moisture (Poulikakos et al., 2006; McLaughlin and Goetz, 1955; Zube, 1962).

Chen et al. (2004) and Caro et al. (2008a) classified the air voids system of asphalt pavements into effective, semi-effective, and impermeable in terms of their effectiveness in allowing the passage of water through them. Figure 2-6 shows the three classification categories of asphalt pavement air voids systems. The effective air voids system has connected air voids channels through the asphalt layer from the top to the bottom of the mix allowing the passage of moisture through it.

Figure 2-6 Air Voids Classification and Asphalt Pavement Permeability (Caro et al. 2008a)

Table 2-2 shows the classification of the asphalt pavement air voids in terms of a typical range of permeability values and mix types. Not all voids in the HMA are permeable to water. The implication is that a given mix might have an acceptable density. However, it could be excessively permeable and less durable. The studies of Hall and Ng (2001); Huang et al. (1999); Kanitpong et al. (2005); Mallick and Daniel (2006), and Mallick et al. (2001)

lay credence to this notion and provided an explanation as to why coarse-graded mixes have higher permeability at a comparable air voids level with fine-graded mixes.

Table 2-2 Classification of Air Voids in Terms of Permeability and Mix Types (Chen et al. 2004)

<i>K(cm/s)</i>	<i>Permeable Condition</i>	<i>Void</i>	<i>Mix Type</i>
10^{-4} -Lower	<i>Impervious</i>	<i>Impermeable</i>	<i>Dense</i>
10^{-4} - 10^{-2}	<i>Poor Drainage</i>	<i>Semi-Effective</i>	<i>Stone Mastic Asphalt</i>
10^{-2} or Higher	<i>Good Drainage</i>	<i>Effective</i>	<i>Porous Asphalt</i>

2.2.3 Permeability and Gradation

Graduation is one of the crucial factors that affect the permeability of asphalt concrete pavement (Anani et al., 1989; Haveem, 1940). Coarse-graded mixes have higher air voids, void connectivity and permeability compared to fine-graded mixes at comparable air voids level (Chen et al., 2017; Choubane et al., 1998; Kanitpong et al., 2001; Mallick and Daniel, 2006; Mallick et al., 2001; Mallick et al., 2003; Masad et al., 2006; McLaughlin and Goetz, 1955). Figure 2-7 shows the field permeability and air voids of different mix gradations according to Mallick et al. (2001). This was also found to be true for laboratory-measured permeability and has been confirmed by numerous researchers (Yan et al., 2016, Mallick and Daniel 2006).

Figure 2-7 Permeability and Air Voids of Different Gradations (Mallick et al 2001)

Research findings have shown that mixes utilizing different combinations of aggregates passing (%P) sieve No. 8 (2.36 mm) as criterion have lower permeability than those that do not. This explains why mixes utilizing coarser aggregates below the maximum density line have higher permeability at comparable air voids levels than others (Kanitpong et al., 2001, 2005; Prowell & Dudley, 2002; Russell et al., 2005). The internal structure of HMA depends on the gradation and the orientation of the different aggregates blend used for the asphalt concrete, and hence, the void structure of the mix. The amount of aggregates passing sieve No. 8 (2.36mm) could be used in mix design to control asphalt pavement permeability. Kanitpong et al. (2005) and Russell et al. (2005) found that the higher the ratio of (%P1/2-%P3/8) to (%PNo.4-%PNo.8), the lower the permeability. Where the Ps are the percentage passing the designated sieves. This suggests that the relative differences in percentage passing of these sieves may affect the internal structure and the measured permeability of the compacted asphalt pavement. As the NMA increases, the size of air voids within a pavement is also likely to increase, especially in

coarse-graded Superpave mixes compared to less coarse Marshal mixes (Mallick et al., 2003; Washington DOT, 2005). More so, gradation and its relationship with asphalt pavement permeability depend on aggregates types and sources. For instance, asphalt concrete made of granite aggregates has higher permeability compared to those made of limestones. However, there are no consistent and conclusive findings on the effect of void in mineral aggregates on the permeability in the literature (Abdullah et al., 1998; Kanitpong et al., 2001; Russell et al., 2005).

2.2.4 Permeability and Internal Structure of Asphalt Concrete

The internal structure of asphalt concrete is an important factor that affects the permeability of asphalt pavements. Physical properties of the aggregates such as size (dimensions), shape, texture, angularity, and tortuosity were found to be the main determinants of the asphalt pavement internal structures based on various studies using imaging techniques such as X-ray computed tomography (Masad et al., 2002, Mahmoud et al., 2010; Zhao et al. 2019; Król et al., 2018 and Kutay et al., 2011). Masad et al. (2002), Kassem (2008) and Liu et al. (2018) observed that compaction is a key factor that determines the shape, pore sizes and the air voids distribution characteristic within the mix using X-ray computed tomography (X-ray CT scan).

The characterisation of the asphalt pavement internal structure helped establish the notion of the interconnectivity of the voids and permeability. Zhao et al. (2019) studied the internal structure of porous asphalt concrete (PAC) and concluded that while all voids in the PAC were interconnected, only 82.1% of the interconnected pores were valid for permeability. Valid voids are the linked air voids system in the asphalt mixture with both ends connected to external space for water passage according to Zhao et al. (2019). Król

et al. (2018) established the relationships between permeability and the air voids system of PAC using X-ray CT scan techniques. They categorised the air voids into total, active and passive air voids based on their connectivity and ability to influence permeability. They found that a change in the cross-sectional size/area of active air voids has a considerable effect on the value of the coefficient of permeability of PAC both in the horizontal and vertical directions. They also observed that both horizontal and vertical permeability coefficients increased with an increasing percentage of active air voids and the length of the pore cross-section (Król et al., 2018 and Kutay et al., 2007). While imaging techniques are useful tools that help with the understanding of the internal structure of asphalt pavement in relation to permeability, they are, however, very costly, time consuming, and require expensive training and labour.

2.2.5 Permeability and Longitudinal Joint Construction Practices

Owing to constructional and operational constraints, asphalt pavement sections (lanes) are usually partially paved at a time across the road width (lanes) and thereafter to be completed with an overlapping joint between the old-paved and the newly paved width in the travel direction. The joint is usually termed the “longitudinal joint” and could be seen as a discontinuity because there always exists a seam between the intersection of the lanes that were placed at different times. Asphalt concrete longitudinal joint quality control and performance have been a subject of discourse over the years. The unrestrained edge of the first lane and the lateral movement of the hot mix during compaction causes the joint to lose heat quicker and attain cessation temperature. Because the edge is unrestrained under compaction load (pressure) of the roller, the asphalt material dilates or shifts outwardly, causing the edges to have less lift thickness and density, as well as higher

permeability values compared to other sections of the lane width making it the weakest part of the road section. It is a widely held view that the weaker and less dense longitudinal joint is the major culprit and causative factor to deep potholes, cracking and ravelling along the longitudinal section of the highway. Additionally, low density and high permeable joints permit the flow and infiltration of water into the rest of the pavement sections (Kandhal and Mallick, 2007; Mallick and Daniel, 2006; Chen et. al., 2013 and Williams, 2011).

Various combinations of joint construction and compaction practices have been studied and investigated to determine the best in terms of asphalt pavement longitudinal joint performance. Some of the joint construction techniques include an infrared joint heater, various joint sealants (adhesives) and compounds, notched wedge, restrained edge, joint bond stabilizer, modified tack coat applied to the longitudinal joints, hot overlap, hot pinch, raking & luting, echelon paving, cutting wheel, joint maker, joint heater, New Jersey wedge, and cold roll (OHMPA, 2013; Fleckenstein et al., 2002; Kandhal and Mallick, 2007; Mallick & Daniel, 2006; Williams, 2011). Major findings by Fleckenstein et al. (2002) and Mallick & Daniel (2006) indicate that although, the joint maker technique and adhesive treated joints had the lowest densities of all the joint improvement methods studied; they had lower permeability values and the best performance under long-term performance study compared to joint constructed using the conventional methods. Similar findings by Wang et al. (2016) and Williams (2011) suggested that while asphalt pavement longitudinal joint treated with the joint stabilizer using polymerized emulsion products had the least density; it ironically had the best performance. Thus, one would argue that the

ability to limit the intrusion of water into the body of the asphalt concrete could lead to a better performing and more durable pavement system.

2.2.6 Permeability and Compaction of Asphalt Concrete

Compaction of asphalt concrete is the process of packing the various particles that constitute the mix closer to one another to reduce interparticle interstices and increase stability under load using external energy and usually by mechanical means. It is considered to be the single most important construction control that will provide for the long-term serviceability of asphalt pavements (Hughes, 1989; Noel, 1977). Asphalt pavement properties such as strength, durability, resistance to deformation, resistance to stripping, impermeability, and skid resistance are pavement properties that are influenced by compaction (Kassem, 2008; Darban, 1993; Finn & Epps, 1980; Hughes, 1989; Linden et al., 1989).

Compaction can be done in the laboratory or in the field during pavement construction. The laboratory compaction could involve blows of the samples confined in a mould as in the Marshall design method (IOWA, 2005). Another method of laboratory compaction involves the gyratory compactor, such as with Superpave mixes, which applies a kneading pressure to compact the loose asphalt mix. Some laboratory compaction methods could also involve the vibratory method according to Brown et al. (2004) and Plati et al. (2016). The slab-roller method as described in Airey and Collop (2016) is another laboratory compaction method that was found to better mimic field compaction compared to gyratory and vibratory methods. Furthermore, Liu et al. (2019) compared the mechanical response of asphalt mixtures manufactured by the Marshall compaction method and a newly developed method called Aachen compaction. Aachen compaction method was

found to better correlate with field samples than the Marshall compaction method. Figure 2-8 is the schematic diagram of the Aachen laboratory compactor as shown in Lui et al. (2019).

Figure 2-8 Operating stages of Aachen Compactor. (a) ram and pre-rolling stage; (b) main compaction stage; (c) lifting stage (Liu et al., 2019).

An entirely different method is the segmented roller as reported in Wistuba (2016). This method could compact parallelepiped specimens in a mould mounted on a sliding carriage under a controlled force or displacement modes to simulate field compaction procedure. Figure 2-9 is the schematic diagram of the German laboratory segmented steel roller according to Wistuba (2016). The primary goals of laboratory compaction methods are to select proper mix designs among other alternatives based on design criteria and to replicate asphalt pavement volumetric and mechanical properties that are obtainable in the field. Hence, standard mix design procedures are differentiated on their method of compaction, which is assumed to simulate field compaction (Khan et al., 1998).

Figure 2-9 German Laboratory Segmented Steel Roller Compactor (Witsuba 2016)

On the contrary, conventional field compaction involves the utilisation of a train of rollers which may include one or more combinations of static, vibratory, or oscillatory rotary steel drum compactor, and the rubber-tired pneumatic rollers. Important distinguishing features of the field compaction compared to the laboratory counterpart are that the hot viscous concrete is not restrained or contained in the mould and compaction is usually achieved with a set of rollers or tires instead of a falling hammer or a ram. Hence, during compaction, asphalt mixtures tend to move laterally and shove in the direction of rolling amidst rapid heat loss. Meeting field characteristics of asphalt pavement using laboratory samples has always been a huge challenge. Khan et al. (1998) concluded that the Gyratory Shear Compaction angle of gyration 1.25° method best represented the engineering properties of the field cores compared to the following compaction methods:

(a) Marshall Automatic Impact Compaction, (b) Marshall Manual Impact Compaction, (c) California Kneading Compaction, (d) Gyratory Shear Compaction angle of gyration 1.2°, and Gyratory Shear Compaction angle of gyration 6°. Consuegra et al. (1989) investigated the ability of different laboratory compaction methods in reproducing field properties of their corresponding counterparts. The authors observed that while the Texas Gyratory compactor was the closest in reproducing field properties based on laboratory cores, the Marshall compactor was the farthest in doing the same amongst the various methods considered. Table 2-3 shows the different laboratory compaction methods compared to their respective field cores according to Consuegra et al. (1989).

Table 2-3 Summary of Average Differences Between Field Cores and Laboratory-Compacted Specimens (Consuegra et al., 1989).

<i>Compaction Device</i>	<i>Creep Compliance at 77°F</i>	<i>Indirect Tensile Strength</i>	<i>Tensile Strain at Failure</i>	<i>Resilient Modulus</i>
<i>Arizona Compactor</i>	<i>0.77</i>	<i>0.51</i>	<i>0.47</i>	<i>0.41</i>
<i>Marshall Harmer California Kneading Compactor</i>	<i>0.8</i>	<i>0.35</i>	<i>0.45</i>	<i>0.55</i>
<i>Steel Wheel Simulator</i>	<i>0.59</i>	<i>0.21</i>	<i>0.27</i>	<i>0.42</i>
<i>Texas Gyratory Shear Compactor</i>	<i>0.51</i>	<i>0.31</i>	<i>0.11</i>	<i>0.26</i>
	<i>0.44</i>	<i>0.14</i>	<i>0.16</i>	<i>0.37</i>
<i>Note: A zero difference indicates that the laboratory specimens had identical properties of the field cores (no difference)</i>				

While specifications for quality control have changed from the “method based” to the “end-result” based; the method of field compaction has remained essentially unchanged for over 140 years since the first field compactor was invented (Geller, 1984; Hughes, 1989; Parker, 1960). From the late 19th century when the first steam roller was invented till the late 1950s, compaction of asphalt concrete was performed by the static rotary steel

drum roller with different axle configurations (Hughes, 1989; Geller, 1984; Parker, 1960). The 1960s saw the introduction of the vibratory steel drum roller, and the oscillatory steel drum roller was introduced between the 1980s and 1990s with a view to improving the efficiency of field compaction and provide better performing asphalt concrete pavements. Figure 2-10 shows the three main technologies of rotary steel drum compactors according to Kearney, (2006).

Figure 2-10 Different Types of Rotary Steel Drum Compaction Equipment (Kearney, 2006)

For several decades, the problems of the “*bow wave*” phenomenon; the resulting surface irregularities and transverse cracks otherwise known as “*roller checking*” have been well documented in the literature. Authors such as Parker (1960) and Geller (1984) have attributed these problems to mix instability and emphasized the training and discipline of the roller operators and increasing the radius of the steel drum as the main panacea to these problems. Figure 2-11 shows the outline of wedge formation and steel drum contact during compaction while Figure 2-12 shows the illustrations of the influence of roller drum radii on the surface irregularities and cracking of the pavement during compaction. Equation (2.0) according to Parker (1960), shows that eliminating the drawbar pull requires an infinite radius of the drum roller i.e. a flat surface. Where P is the drawbar pull which simply signifies the engine pull or track force, W , the weight of the roller, G , is the cord

length of the arc subtended by the rolling contact, R , radius of the drum and H the depth of drum penetration into the hot asphalt during compaction.

Figure 2-11 Wedge formation (a) and (b) outlined of steel drum contact during compaction (Parker, 1960).

Figure 2-12 Influence of Roller Drum Radius on Surface Irregularities of Asphalt Concrete (Parker, 1960)

Equation

$$P = \frac{WG}{R - H} \quad (2.0)$$

The drawbar pull, through the effect of steel drum material and geometry, interacts with the semi-solid asphalt concrete during compaction and produces compacted asphalt concrete pavements that have connected air voids and highly permeable surfaces (Abd El Halim, 1985; AbdelHalim et al., 2015; Gogula et al., 2003; Hussein et al., 1993; Ingles, 1993; Tarefder & Ahmad, 2016).

As mentioned earlier, Equation (2.0), indicated that removal of the effect of the drawbar pull, which causes surface cracks, entails having an infinite radius of the steel drum roller. This condition can be achieved by replacing the drum with a flat surface such that the pavement is compacted without initiating cracks. Asphalt Multi-Integrated Roller (AMIR) compaction technology has been developed under this premise to solve the problems of asphalt surface cracking during compaction operations by using soft flat surface in compaction following the principles of relative rigidity (Abd El Halim, 1984; Abd El Halim and Mostafa 2006; Mohamed et al.1993; Abd El Halim et al. 1996; Abd El Halim and Bauer, 1985). Figure 2-13 shows the schematic diagram of the AMIR and the conventional steel drum compactor as well as their interactions with the pavements.

Figure 2-13 The Schematic Diagram of (A) AMIR and (B) Steel Drum Rollers

AMIR efficiently compacts asphalt concrete pavements and produces surfaces that are free of cracks and irregularities, with low permeability, and with improved engineering properties; all of which lead to better durability and long-term performance (Abd El Halim et al. 2013; Abd El Halim et al. 1988; Abd El Halim, 1984; Abd El Halim & Abdelzaher, 2006; Abd El Halim et al., 2009; Abd El Halim et al., 1996; Mohamed et al., 1993; Igboke et al., 2018; Omar et al., 2018; Said et al., 2008).

From the foregoing paragraphs, it can be deduced that the method of compaction both in the laboratory and in the field has a profound influence on the resulting properties of compacted asphalt concrete including permeability controlling for other variables. The

microstructure and the resulting void distribution of the compacted asphalt concrete are greatly influenced by the compaction methods used. This explains the discrepancies and differences often reported between permeability measurements of field and laboratory compacted asphalt mixtures of the same mix design (Igboke et al., 2018; Kanitpong et al., 2005; Omar et al., 2018; Russell et al., 2005; Tarefder & Ahmad, 2017; Tarefder and Ahmad, 2016).

Similarly, Tarefder & Ahmad (2016) observed that the pore structure of field compacted samples is totally different from linear kneading and gyratory laboratory compacted samples. Permeability of field samples does not depend on the level of compaction as much compared to the laboratory compacted samples. This agrees with the findings of (Cooley & Maghsoodloo, 2002). In general, Brown et al. (2004) concluded that laboratory specimens compacted with vibratory compactor have lower permeability than the specimens compacted with the gyratory compactor which is in agreement with the findings of (Russell et al., 2005). These differences in permeability of different compaction methods result from the geometry, the boundary conditions of the interfaces of the asphalt concrete material and the compactor, density gradient and the orientations of the aggregate particles of the mix. It is important, therefore, that the permeability of asphalt concrete in relation to the compaction method and several factors that influence permeability to be studied, defined, and benchmarked.

2.2.7 Summary of Relationship between Permeability, Density, Air Voids, and Compaction

From the aforementioned reviews, the permeability of asphalt concrete ordinarily increases with a higher air voids level. However, there are disagreements in the literature

on the effect of air voids on permeability for different asphalt mix types especially for field compacted samples (Awadalla et al., 2017; Brown et al., 2004). Research findings suggest that low permeable asphalt concrete pavement is not necessarily related to high density and by extension high pavement performance characteristics. This indicates that permeability of asphalt concrete could be a better pavement quality indicator (Brown et al., 2004; Fleckenstein et al., 2002; Hainin et al., 2013; Hall & Ng, 2001; Mallick & Daniel, 2006; Owusu-ababio et al., 2009; Russell et al., 2005). The compaction method plays the most vital role in pavement performance because it influences the distribution, orientation of aggregates of different sizes, and connectivity of the voids in total mix, and the issue of dimensions of flow and material anisotropy (Awadalla et al., 2017; Bhattacharjee & Mallick, 2002; Choubane et al., 1997; Caro et al., 2008a; Hall & Ng, 2001; Mohamed et al., 1993; Kandhal and Mallick, 2007; Mallick & Daniel, 2006). It, therefore, suggests that the current convention of using density as a criterion for job acceptance is deficient and that the permeability of any mix is unique and field-specific and should be incorporated in the asphalt pavement quality control protocols (Hainin et al., 2013; Kandhal and Mallick, 2007; Brown et al., 2004).

2.3 Measurements of Permeability of Porous Media (Asphalt Concrete)

In 1856, Henry Darcy, a French civil engineer, established the fundamental concept of permeability otherwise known as hydraulic conductivity. Darcy investigated the flow of water through sand filters, and the parameter of his experiment was called hydraulic conductivity (Darcy, 1856). The permeability is the time rate of flow given specified boundaries and some idealized conditions. Mathematically, permeability is proportional to the hydraulic gradient. Figure 2-14 shows the schematic of one-dimensional Darcy's law

which forms the concept of permeability or hydraulic conductivity according to Das (2007).

Figure 2-14 Schematic Diagram Illustrating Darcy's Law (Das, 2007)

The permeability in Darcy's law can be written as given in Equation (2.1) below;

Equation

$$k = \frac{Q}{Ai} = \frac{QL}{A(h_2 - h_1)} \quad (2.1)$$

Where Q = volumetric flow rate (m^3/s), k = permeability coefficient (m/s),

A = cross – sectional area of the specimen (m^2),

L = thickness of the specimen (m)

h_2, h_1 = final and intitial water level (head) measured to a datuam (m)

However, the application of Darcy's law of permeability holds under certain ideal conditions which include (a) flow is continuous (b) flow with the voids fully saturated, (c) steady-State flow and (d) flow must be laminar. Consequently, to measure asphalt pavement permeability; a good number of permeameters have been developed and used to measure asphalt concrete permeability in the field, and in the laboratory, with some using air as the test fluid while others employ the use of water. The air-based permeameters include but are not limited to Kentucky Air Induced Permeameter (AIP), Kuss Vacuum Permeameter and Romus Air Permeameter. Those that employ the use of water include Kuss Constant Head Permeameter, NCAT (National Centre for Asphalt Pavement Technology) permeameter, ASTM C1701 permeameter to mention but a few (Brown et al., 2004; Choubane et al., 1998; Cooley, 1999; Cooley et al., 2001; Cooley & Maghsoodloo, 2002; Hall, 2004; Mallick et al., 2003; Schmitt et al., 2007; Li et al., 2013).

More so, an important aspect of field permeability measurement is to consider the effect of traffic i.e. tire pressures and speed of vehicles on pavement permeability termed hydraulic scouring and pumping (Wang. et al., 2019; Kutay and Aydilek 2007). This usually results in the deposition of colloidal fines into the body of the asphalt concrete which accelerates moisture damage and other forms of distresses and prevents rejuvenation and healing (Zube, 1962; Standiford et al., 1985 and Wang et al. 2019). The traditional method used to estimate moisture damage of asphalt pavements employs static conditioning of freeze-thaw cycles. Moisture sensitivity is then quantified by a change in physical and mechanical properties before and after the conditioning (Wang et al., 2019; Mallick & Daniel, 2006; Tardier and Ahmad, 2015). Figure 2-15 shows the schematic diagram of hydraulic scouring induced by the interaction of the tire and pavement structure.

Figure 2-15 A schematic diagram of hydraulic scouring induced by the interaction between a vehicle tire and the surface layer of asphalt pavement (Wang et al., 2019).

Hence, the permeameters are categorized into two, static and dynamic permeameters (Coleri et al., 2014; Standiford et al., 1985; Zube, 1962). Static permeameters (permeameter that obey Darcy's ideal flow conditions) measures permeability in the hydrodynamic range that occurs at the vehicle speed of 40 mph (64 km/hr) while the dynamic permeability is measured above the hydrodynamic pressure range. The hydrodynamic pressure range is seen to be practically relevant to heavy load traffic and to the airport pavement due to the weight, speed, and tire pressure of aircrafts. Highway vehicles typically generate pressures in the range of 90 to 283 kPa (13 to 41

lb/square inch) while a Type VII aircraft could generate a tire pressure of up to 1379 kPa (200 lb/square inch) or more (Standiford et al., 1985).

2.3.1 Air Permeameters

Air permeameters use air as the conducted fluid through the porous media (asphalt concrete) to measurement permeability. Some of the air permeameters were devised to measure and correlate the measured air-permeability and calculated porosity of specimens directly taken from the completed asphalt pavement sections. Other air permeameters directly measure permeability in the field to avoid the enormous work and cost that may be associated with field coring. Ekse and Zia (1953) developed an air permeameter based on the hand-pumped pressure decay time of a chamber from 4 psi to 0.5 psi with the asphalt concrete samples acting as a barrier to airflow to directly measure field permeability of the compacted asphalt pavement sections to avoid field coring of samples. This pressure decay curve was used as a surrogate to correlate the porosity of the field compacted mix.

McLaughlin and Goetz (1955) devised a means of measuring the air permeability of sand-asphalt mixtures and to study the relationship between the air permeability and the sonic modulus of the cores. The permeameter could produce a pressure of 3000 mm of mercury. A related method was used by Ellis and Schmidt (1961) to measure field air permeability of asphalt concrete based on the differential pressure of water. Figure 2-16 shows the diagram of the apparatus according to (Ellis and Schmidt, 1961). Measurements are made by adjusting the stopcock so that the vacuum pressure as shown on the manometer is constant at the desired level. The volume of water at an instance through the pipet equals the volume of air coming through the pavement from the dome and by timing, flow rates are calculated. The device can also be adapted for laboratory measurements on cores for a

wide range of permeability values by using a glass dome, a core adapter and a rubber sleeve to house the core during testing.

Figure 2-16 Schematic Diagram of the Permeability Apparatus (Ellis and Schmidt, 1961)

A dynamic air permeability device developed by Pennsylvania State University uses a compressed air tank, a pressurized chamber with pressure regulators, ball valves and a blast of pressurized air (90-283 kPa) from the discharge chamber into the pavement. The pavement-device interface employs the use of available sealants applied in a 3.18 mm diameter strand (Standiford et al., 1985). The schematic of the apparatus according to Standiford et al. (1985) is shown in Figure A.1 in Appendix A.

Furthermore, the Pennsylvania State University developed a static air permeameter that consists of three compressed air tanks, a double air regulator, air filter, one-off switch, three precision metering valves, five airflow meters, and a pressure gauge. It employs the use of pressurized air input at a constant pressure to measure airflow through pavements. It also uses commercially available sealants and meets the ideal flow conditions and correlates well with static water permeameters. Furthermore, its results are repeatable, easy to use and could last longer (Standiford et al., 1985). However, the components and assembly are complex, costly and mobility for field application is cumbersome. Figure A. 2 in Appendix A shows the schematic of the static flow meter.

Similarly, ASTM (American Society for Testing and Materials) developed a static air permeameter that measures the rate at which pressurized air can be drawn (vacuum system) through a pavement. It uses a soft rubber ring at the pavement-device interface sealing. It also has a pressure control device, a manometer, and a laboratory cell. The equipment and testing procedure of measuring pavement permeability do not meet the ideal flow conditions because the equipment constantly produces decreasing air pressure which should be compensated to obtain accurate flow rates (Standiford et al., 1985). The schematic of the apparatus is shown in Figure A. 3 in Appendix A. The equipment can also be adapted to be used to measure permeability both for field and laboratory specimens by using a specially built cell.

California Research Corporation (Subsidiary of Standard Oil Company) also developed an air permeameter that was field-tested by the Pennsylvania State University. This device is also similar to the one used by (Ellis & Schmidt, 1961) except for the pavement-device interface assembly which employs a grease pump for the sealing of the

interface. This device was found to have some disadvantages. It required at least a minute to obtain a quantity of flow that is then timed and converted to flow rates. It has a maximum output pressure of 305mm (12 inches) of water and the stopcock must be large enough to create sufficient pressure to be detected by the manometer, even though it has good repeatability and could as well be adapted for field and laboratory uses (Standiford et al., 1985).

An Air Induced Permeameter (AIP) was developed by the Kentucky Transportation Centre. The device consists of a digital vacuum gauge that can read a pressure range of 0-700 mmHg and a multi-venturi cube attached to the top of a sealed tube (encasement) with an internal diameter of 8 inches. A 3-inch diameter sealing ring is used to aid device-pavement interface sealing by the application of silicone sealant. A multi-venturi is a series of nozzles arranged from the largest to the smallest nozzles through which pressurized air passes at constant pressure. Reading is taken by forcing air out of the pavement at a constant pressure of 68 psi through a multi-port venturi meter until a constant reading is maintained on the digital readout. The higher the vacuum pressure, the lower the permeability and vice versa. One major drawback of the device is that the measured AIP needs to be correlated with water-based permeability for measurements to be meaningful, although cheap, portable and very repeatable. Another major problem with the use of this equipment in the field is the potential humping or delamination of the pavement layers if allowed to run for a long time (Allen et al., 2001). Figure 2-17 shows the field installation of the air induced permeameter (AIP).

Figure 2-17 Air Induced Permeameter Field Installation (Allen et al., 2001)

The Kuss vacuum permeameter device employs a straightforward way of empirically mapping out of an area, density, and void connectivity of a pavement surface. It consists of a large, clear encasement that is connected to a vacuum pump or source. The encasement is made of Plexiglas 0.5-inch-thick; it measures 23 in. by 23 in. by 3.5 in. and uses a strip of foam for leak proofing at pavement-device interfaces. The test is performed by selecting a 14-inch square pavement surface which is marked usually in a definite square pattern. The pavement surface is saturated, and encasement is centred over the testing area. The vacuum is then applied, the encasement is thereafter sealed to the pavement surface and air bubbles develop where connected voids exist on the pavement surface and allowed for about 15 minutes to establish a regular and consistent bubble pattern and thereafter, the area is mapped out. The percentage gives an indication of the air permeability of the pavement surface (Williams, 2007). Although this device does not directly measure permeability, it gives the percent area of the pavement that is permeable to air. One problem with this method of measurement is that is complicated, tedious, and costly as it involves

video recording for the surface mapping in order to determine the area of the pavement that is air permeable. Figure 2-18 shows the field application and typical result of the Kuus Vacuum Permeameter.

Figure 2-18 Kuus Vacuum Permeameter Field Installation and Processed Result (Williams, 2007)

The ROMUS falling head air permeameter was developed at Marquette University. It consists of a vacuum chamber, base seal reservoir, automatic pump, automatic valve, digital pressure gauge, and a digital display. Testing is initiated after sealing the device to the pavement using a grease seal. The grease is manually pumped into a recessed base ring for fluid containment and to serve as an improvement to fluid containment problems associated with NCAT permeameter by levelling and normalizing surface irregularities. Pressing the start button initiates an automated system of operation that creates a vacuum within the internal pressure chamber of more than 24 inches of water (45mmHg) which is the maximum head of water used for NCAT permeameter. A valve then automatically opens to allow air to flow through the pavement layer into the vacuum chamber and a

timing system is initiated. Air is continuously drawn into the vacuum chamber until the internal pressure approaches the atmospheric. Timing records for pressure drop mimicking the drop of the head in NCAT permeameter of 4 intervals (24 to 20, 20 to 16, 16 to 12 and 12 to 8 inches). Permeability is calculated based on the falling head principle following Darcy's law according to Equation (2.2) (Awadalla, 2015; Menard & Crovetti, 2006; Retzer, 2008).

$$\text{Equation} \quad K = \frac{LV\mu}{ATP_a} \ln \frac{P_1}{P_2} \quad (2.2)$$

Where K = *absolute permeability* (m^2) which is independent of the media and fluid, L = *pavement layer thickness* (m), V = *volume of the vacuum chamber* (m^3), μ = *dynamic viscosity of air* ($kgm^{-1}S^{-1}$), T = *time of head drop* (S), A = *area of being tested* ($0.01824 m^2$), P_a = *atmospheric pressure* $kgm^{-1}s^{-2}$, P_1 = *initial pressure* (m), P_2 = *final pressure* (m). The actual permeability coefficient is obtained according to Equation (2.3) given as;

$$\text{Equation} \quad k_w = K \frac{\rho_w g}{\mu_w} = \frac{LV\mu}{ATP_a} \frac{\rho_w g}{\mu_w} \ln \frac{P_1}{P_2} \quad (2.3)$$

Where every other symbol retains its previous meanings whereas k = *hydraulic permeability* (cms^{-1}), g = *acceleration due to gravity* ($kgms^{-2}$) and μ_w = *dynamic viscosity of water* ($kgm^{-1}S^{-1}$). Figure 2-19 shows the schematic diagram of a ROMUS air permeameter.

Figure 2-19 Schematic of The ROMUS Air Permeameter (Retzer, 2008)

One major concern with the permeability measurement with ROMUS air permeameter is that even though the problem of saturation is evident with NCAT permeameter, permeability measured with ROMUS air permeameter appears to be higher on average than those reported by NCAT for typical mixes tested. This questions its validity and applicability to the moisture permeability of asphalt pavement especially as it relates to the applications of the ideal flow conditions and using fluid properties of air to estimate that of water (Menard & Croveti, 2006; Standiford et al., 1985).

2.3.2 Water Permeameters

Zube (1962) used a grease ring to dam a measured volume of water and a two-minute duration required for a glistening surface appearance represents permeability. This method of measuring permeability means that reading is being taken as water is being absorbed, and the criteria to determine a “glistening” surface is not specific. Also, the boundary line between permeability and evaporation is very thin for the quantity of water used in hot and windy weather. McLaughlin and Goetz, (1955) used water for the determination of the permeability of asphalt pavement cores. However, the device is mainly adapted to laboratory measurements and the process of taking a reading is time-consuming and tedious.

A dynamic permeability device that uses an explosive to produce a dynamic pressure on a rectangular piston (16,129 square mm) which forces the piston and the fluid beneath the piston to move into the asphalt pavement was reported by Standiford et al. (1985). This system is likened to the hydrodynamic pressure under an aircraft tire on hydroplaning speed. The use of this equipment does not apply to highway pavement, and moreover, there were issues about the validity of the test measurements as the ideal flow conditions may not be met. Figure A. 4 in Appendix A shows the schematic diagram of the dynamic water permeameter. Similarly, an experiment was made with Moore's outflow water permeability meter. It was used to measure the surface drainage capacity of the laboratory specimen. This was later modified by pressurizing the water cylinder and surcharging with air pressure. This later was further modified for water containment at the device-pavement interface by Birmingham University. Figure A. 5 in Appendix A shows the schematic diagram of the permeameter. It consists of a transparent cylinder with a hole

on the pavement contact end through which water outflow is regulated. The device has a rubber ring and weight applied to the top for fluid containment. This device was based on the falling head principle to measure a combined flow of water through a tested surface. Measurements are repeatable but no comparison with other devices was done to check for correlation (Lees & Katekhda, 1974; Standiford et al., 1985).

In the same vein, a water-based static permeameter was developed by the Army Corps of Engineers Waterways Experiment Station (WES) according to Figure A. 6 in Appendix A. It was simple and consists of a transparent cylinder with an inflow valve, a rubber ring, and a load gauge. It could be used on falling or constant head principles. Permeability is measured as a flow rate in constant head mode by calibrating the scale of settings for the variable-flow pump used to maintain the constant head. The rubber ring seals between the device and pavement by an applied load from a vehicle. No correlation was made of this device with others. However, it was reported that it had good repeatability and portable (Standiford et al., 1985; White, 1975; White, 1976).

Another water-based permeameter based on the constant head principle was developed at the University of Arkansas, known as Kuss constant head permeameter, and is illustrated in Figure 2-20. The device is sealed to the pavement surface and water is added thereafter to the standpipe and allowed to flow through the pavement depth. The device has an area of 14 (square inch) or (99,315 square mm). A water level sensor is connected to a flow valve in the flow meter box. As water flows across the pavement thickness, causing the water level to drop, the water level sensor trips the flow valve which in turn measures the equal volume of air to occupy the volume of receding water. It is assumed that in this method, a constant head is maintained. Permeability is calculated by

using the volume of water entering the pavement over a given period and the exposed cross-sectional area is given by Equation (2.4).

Equation
$$k = \frac{QL}{Ah} * t_c \quad (2.4)$$

Where k is the permeability coefficient, Q is the flow rate, L pavement thickness, A is the samples area, h is the height of water column and t_c is the correction factor for the temperature of the water.

Figure 2-20 Kuss Constant Head Field Permeameter (Awadalla, 2016)

One major drawback of the device is that the true constant head is difficult to maintain as air is used to make up for the falling head of water which has a different density from that of water hence cannot account for the pressure head of water during the test. Also, results have shown that it is difficult to use this device to measure pavement with low permeability as compared to NCAT permeameter due to insufficient pressure head of

water. Another problem with this method of measurement of permeability is that it is significantly affected by the problem of absolute saturation (Awadalla, 2015; Hall, 2004).

In late 2009, the ASTM C1701 test method of measuring field permeability was developed to measure pervious concrete in the field (Chen et al., 2019 and Wang et al., 2019). According to Li et al. (2013), the test procedure involves securing the device to the pavement surface using a recommended sealant. Then, the pavement is pre-wet by pouring about 3.6 kg of water into the ring at a rate sufficient to maintain a head between marked lines at a distance of 10 to 15 mm from the bottom until the 3.6 kg of water has been used. Timing is initiated once the water impacts the pervious surface and stopped when free water is no longer present on the pervious surface. Run the actual tests by repeating the preceding steps using 3.6 kg water if the pre-wetting elapsed time is greater than or equal to thirty seconds, otherwise use 18 kg of water. The mass of water used is recorded and permeability (infiltration rate) is calculated with Equation (2.5) as follows;

$$\text{Equation} \quad k = \frac{CM}{D^2t} \quad (2.5)$$

Where k is the infiltration rate, mm/h; M is the mass of infiltrated water, kg; D is the inner diameter of infiltration ring, mm t is the time required for a measured amount of water to infiltrate the pavement in seconds, and C is the constant value, 4,583,666,000, in SI units.

Figure 2-21 shows the schematic diagram of the ASTM C1701 permeameter and its field application. The problems with ASTM C1701 are that its operation is plagued with the drawbacks of other permeameters as outlined earlier. Furthermore, the head and size of the device are grossly inadequate for field application of highly permeable surfaces such as asphalt concrete.

Figure 2-21 The Diagram and Picture ASTM C1701 Permeameter

An in-situ permeability known as the Yverdon permeameter according to the Swiss standard was also reported in Poulikakos et al. (2006). According to the authors, the indirect measurement of the flow passing through the sample is determined from the water circulation with a constant flow rate, under the fixed circular base section. The device-pavement interface is sealed off using synthetic mastic in addition to a weight of 70 to 80 kg. The operation of the device is in two stages; the first stage involves varying the water pressure to eliminate air bubbles while the second stage involves maintaining a stabilised water level of 170 mm in 10 seconds. Measurements thereafter are taken using a graduated container and the test gets repeated twice. Permeability is reported in litre per minute as the mean of the repeat tests. It is noted however that Poulikakos et al. (2006) did not provide field measurement results or comparison using this device.

The NCAT permeameter developed by the National Centre for Asphalt Pavement Technology at Auburn, Alabama, USA appears to be most popular owing to its simple operation, repeatability, and cost-effectiveness. It has an exposed area of about (17, 671 square mm) and a diameter of 150 mm. A weight of about 20lb; 4 times 5-lb weight masses,

gasket and commercial sealant are used for fluid containment between device and pavement interfaces. A modification to NCAT permeameter was made by the Worcester Polytechnic by using a weight of 47 kg (110lb) for fluid containment (Awadalla, 2015; Awadalla et al., 2017; Harris, 2007; Mallick and Daniel, 2006). Figure 2-22 shows the field use of NCAT permeameter. Equation (2.6) is the NCAT permeability equation where k is the coefficient of permeability, a is the cross-sectional area of the permeameter burette, h_1 and h_2 the initial and final heads of water, L is the sample or pavement thickness, A is the tester area, T is the test time and t_c is the temperature correction factor for the viscosity of water outside the standard test temperature which is $20^\circ C$.

$$\text{Equation} \quad k = \frac{aL}{AT} \ln \left(\frac{h_1}{h_2} \right) * t_c \quad (2.6)$$

However, there have been concerns and objections to the field permeability measurements using the NCAT permeameter. Essentially, the field permeability measurement does not correlate well with the laboratory-measured permeability using corresponding falling head principles such as the Karol-Warner permeameter (Florida Permeameter). Other major challenges of using NCAT permeameter which is not usually reported are; maintaining a leak-free measurement to ensure accurate results, ensuring that the sealing and caulking works don't alter the effective area of the permeameter exposed to the pavement surface.

Figure 2-22 NCAT Permeameter

Also, the problems of absolute saturation of the pavement, reading, and recording of measurements especially for a highly permeable pavement where the head fall is so rapid are major drawbacks of this permeameter. Other problems include difficulty in installing the device on superelevated surfaces and the surface area not being representative enough to cover sample and surface heterogeneity. Furthermore, the permeameter is made of a very brittle and fragile plastic which makes it crack and break easily when in use (Cooley, 1999; Harris, 2007; Kanitpong et al., 2005; Mallick et al., 2003; Russell et al., 2005).

Furthermore, permeameters that use water for the measurements of asphalt pavement permeability are common, especially in the laboratory environment. A method of measuring permeability in the laboratory that is based on the falling head principle was

developed by Karol-Warner and adopted by the Florida Department of Transport that is standardised in ASTM PS-129-01 (Choubane et al., 1997; Florida DoT 2004; Chen et al., 2013 and Hall 2004). Permeability measurements are taken by allowing water level in a graduated cylinder to fall and pass through a saturated asphalt core sample with its side wrapped in a pressurized flexible wall that is further housed and held in a metallic cylinder with two O-rings (upper and lower) and clamps. The time taken for the water level to fall between established upper and lower timing marks of the graduated cylinder is recorded and used for the calculation of the one-dimensional permeability coefficient according to Equation (2.6). Problems and shortcomings of using the Karol-Warner device include consistently maintaining the sidewall pressure, sidewall leakage, results that were variable and not easily repeatable and the lack of correlation between its measurements and comparable field measurements such as the NCAT device (Kanitpong et al., 2001).

Similarly, ASTM D5084 is one of the standard methods used in the measurement of permeability of asphalt cores in the laboratory reported in the literature and popularly used in geotechnical engineering (Kanitpong et al., 2001; Kanitpong et al., 2005 and Masad et al., 2006). The development of this device was aimed at correcting the deficiencies of the Karol-Warner device. The equipment uses a flexible wall (membrane) in a cell filled with water and a technique termed backpressuring to ensure saturation. Water is delivered to the cell using a pressure panel at specified pressures. The pressure panel also measures the rate at which water flows. Figure 2-23 shows the schematic diagram as shown in Kanitpong et al. (2005).

Figure 2-23 Flexible-wall permeameter and pressure panel board according to ASTM D5084-01 (Kanitpong et al., 2005)

This method can test the permeability of specimens in the constant head, falling head and falling head rising tail method. The permeability coefficient is calculated following Equation 2.7 below.

$$\text{Equation} \quad k = \left(\frac{a_1 a_2}{a_1 + a_2} \right) \left[\frac{L}{A(t_2 - t_1)} \right] \ln \left(\frac{\Delta H_1}{\Delta H_2} \right) \quad (2.7)$$

Where a_1 and a_2 = cross-sectional area of inflow and outflow burettes, respectively, A =

the cross-sectional area of the specimen, and ΔH_1 and ΔH_2 = differences in total head across the specimen at times t_2 and t_1 , respectively.

Details of the method can be found in Kanitpong et al. (2001) and the standard document ASTM 5084 (ASTM 2016). Problems and shortcomings of using the ASTM 5084 permeameter include also the problem of sidewall leakage that has to be solved using bentonite. Also, the operation of the device is complicated and requires termination criteria based on incremental inflow and outflow that exhibits no trend. Finally, the device measures the saturated hydraulic conductivity of porous materials having saturated hydraulic conductivity less than or equal to 1×10^{-3} cm/s according to Kanitpong et al. (2001).

In Europe, attempts were also made to directly measure horizontal and vertical permeability coefficients for the hydraulic assessments of porous asphalt applications as reported in Poulikakos et al. (2006) and Król et al. (2018) following European Standard EN 12697-19 developed by Laboratoire des voies de circulation – LAVOC Lausanne, Switzerland. Vertical and horizontal permeability measurements can be made with this device by changing the orientation and boundary conditions of the tested sample using rubber gaskets. Measurements of vertical permeability coefficient involve applying a column of water at a constant head of 300mm to a cylindrical asphalt specimen at a temperature ranging from 15 to 25°C. Figure 2-24 is the diagram of the horizontal and vertical permeability devices according to Król et al. (2018).

Figure 2-24 Schematic Diagram of Horizontal and Vertical Permeability Devices (Król et al., 2018).

The vertical permeability k_v is calculated from the measured flow rate of water Q_v as following Equation (2.8) below.

$$\text{Equation} \quad k_v = \frac{4Q_v I}{h\pi D^2} \quad (2.8)$$

Where, k_v is the vertical permeability (m/s); Q_v is the vertical flow rate (m³/s); I is the thickness of the specimen (m); h is the height of the water column (m) and D is the diameter of the specimen (m).

The requirements for dimensions of core samples to be tested are; thickness at least a quarter of the diameter and/or at least two times the maximum aggregate size. No correction related to hydraulic conductivity as a function of water temperature is applied. Poulikakos et al. (2006) and Król et al. (2018) also reported a method to measure the

horizontal permeability of asphalt samples following a procedure and standard similar to the vertical permeability. The horizontal permeability k_h is calculated from the measured flow rate of water Q_h as following Equation (2.9) below.

$$\text{Equation} \quad k_h = \frac{Q_h I}{(H + P + 0.5I)(\pi D I)} \quad (2.9)$$

Where, k_h is the horizontal permeability (m/s); Q_h is the horizontal flow rate (m³/s); I is the thickness of the specimen (m); h is the height of the water column (m) and D is the diameter of the specimen (m). H is the distance of the lower and upper tubes (m) and P is the height of the lower tube (m). The requirements for dimensions of core samples are the same as that of the vertical permeability.

Standiford et al. (1985) summarized and categorized types of permeability equipment for static and dynamic measurements of asphalt pavement. Although the dynamic air permeameters appear to measure the permeability of asphalt pavement better; the effects of the compressible nature of air on the measurements were questioned. For static tests, Standiford et al., (1985) concluded that the air permeameters were the most portable and repeatable but questioned their ability to typically measure actual flows through porous media such as porous friction surfaces due to the compressibility of air, continuous and occluded voids of the pavements. Also, a serious objection was made about air permeameters meeting Darcy's conditions for permeability measurements. Again, most methods of measuring permeability using air involve some sort of correlation with water-based permeameter which does not really solve the problems of field measurements of permeability. Findings from the literature suggest that the falling head method of measuring permeability was more suitable than the constant head method because of its

simplicity, realistic appreciation of the variation of permeability of samples and the inability of the latter to allow the flow of water at measurable pressure head (Maupin, 2000, 2010).

2.4 Tester Size, Anisotropy and Extrinsic Factors Affecting Measurement of Permeability

The measurement of field permeability of asphalt pavement has been important as well as controversial. This is partly because, specimen dimension is not usually known exactly compared to the laboratory methods, maintaining uniformity of test conditions and problems of variability and heterogeneity within a mix could be high. Permeability is usually anisotropic; meaning that permeability values in the vertical and horizontal (radial) directions are not essentially the same for materials like asphalt concrete (Harris et al., 2011; Harris, 2007).

Also, the hydraulic gradient is a major factor in the measurement of permeability. There is no definite conclusion on this in the literature. Kanitpong et al. (2001) observed that hydraulic conductivity increases slightly as the hydraulic gradient increases to a modest level and then decreases as it is raised further but concluded it has a negligible effect for asphalt concrete samples. Furthermore, factors such as the testing time and confining pressure are important considerations for the laboratory measurements of permeability. Hall et al. (2000) concluded that the effects of confining pressure and testing time were not significant for the permeability of asphalt pavement. However, it has been shown that confining pressure has a huge effect on the hydraulic conductivity of soil samples such that the hydraulic conductivity decreases with increasing confining pressure for the samples examined (Dafalla et al, 2015). Experiences in the laboratory have shown

that the time rate of change of hydraulic gradient is not constant. The permeability values tend to be higher with higher heads of water. Findings by (Hall, 2004) have shown as well that the NCAT permeameter has higher permeability values than the Kuss constant head permeameter due to the higher head of NCAT permeameter.

Similarly, the tester (device) contact area size with the pavement affects the value of measured permeability in the field. Permeability tends to be lower with increased tester contact area compared with lesser contact area. This factor is equally suggested to be one of the major sources of discrepancies between laboratory and field measured permeability values. This is because with higher tester size; the more the samples are well represented and less the variability within materials (Hall, 2004; Harris et al., 2011; Williams, 2007). It has been shown that the Kuss constant head permeameter has permeability values well correlated with the laboratory values and that the higher the field tester size, the closer the relationship between field and laboratory permeability (Hall, 2004; Harris et al., 2011; Harris, 2007). Figure 2-25 shows the relationship between permeability coefficients and the tester sizes of the device-pavement interface according to Harris et al. (2011).

Figure 2-25 Permeability Versus Contact Area Relationship (Harris et al., 2011)

Finally, one of the most important factors that affect the values of the measured permeability is saturation and it is one of the major ideal conditions to be satisfied for Darcy's law to hold. Although, attaining saturation in the laboratory can be relatively achieved but almost impossible in the field. Experience in the laboratory has equally shown that absolute saturation is potentially impractical if not impossible because the consecutive readings of permeability should remain the same provided that the testing conditions are not changed but this is not always the case especially for Florida or Karol-Warner Method. Permeability values have been observed to change slightly irrespective of the saturation level and time.

2.5 Review Comments and Summary

From the foregoing literature review, compaction is the single most important factor that affects the permeability of asphalt concrete both in the field and in the laboratory controlling for other factors. Although the current asphalt rollers may achieve the specified

level of compaction set by the supervising agency when the right combination and modes are used; they, however, produce pavement structures with interconnected air voids with high permeability and surface cracks at the time of construction. The connected air voids systems and surface cracks at the time of construction are the precursors and culprits to associated pavement distresses which compromise the performance and durability of asphalt pavements. Furthermore, the subject of the measurement of the asphalt pavement permeability is controversial because of the problems of maintaining consistent conditions during the test and varying results, that the use of different types of permeability equipment yield. More so, there are problems in keeping flow conditions and environment the same for every case of the test whether in the laboratory or in the field. Because of the aforementioned issues, making meaningful comparisons between test methods is very difficult. Hence, every field permeability measurement project is unique and specific.

Results of permeability studies of different gradations suggest that at a comparable air voids level, the permeability of coarser gradations is higher than less coarse ones. Reliance on density or compaction level alone may have been the culprit of the asphalt pavement distresses for several decades now. Notwithstanding the potential benefits of air permeameters, obeying flow conditions is of paramount importance in the measurement of permeability to ensure accurate and reliable results which are the major drawback of the current air permeameters. Measuring field compacted samples' permeability in the laboratory involves destructive coring of samples and very intensive and costly labour. It is time-consuming and does not represent field conditions. If permeability is to be incorporated into the quality control scheme and to be used as one of the job assurance and acceptance indicators, it is pertinent, therefore, that we develop efficient and reliable

equipment to measure field permeability at the field construction scale under comparable conditions. This would provide the contractors with ample time to correct or amend relevant aspects of their paving works to ensure quality control compliance and long-term performance of the completed pavements. This study, therefore, proposes and presents a new method of measuring the water level changes and permeability of asphalt concrete with the hope to remediate the drawbacks of the existing permeameters and to efficiently measure field permeability of asphalt concrete pavement for better quality control and durable asphalt pavements.

Chapter 3: Experimental Programme

This chapter presents the outline of experimental investigations used in this research work to study field compaction and permeability related to asphalt quality control in order to achieve the objectives of the thesis as outlined in Section 1.3 of this thesis. Following the research plan briefly discussed in Section 1.4, a comprehensive research plan and programme was developed as shown in Figure 3-1. The aspects of the research are divided into field and laboratory investigations. The field investigations involve employing the mainstream field compaction technologies to compact selected road sections. The compaction technologies include the vibratory train, oscillatory train, and the AMIR (Asphalt Multi-Integrated Roller). The vibratory compaction train involves the various modes of rotary vibratory steel drum roller in combination with the pneumatic or tired rollers. The oscillatory train compaction involves the various modes of rotary oscillatory steel drum roller in combination with the pneumatic or tired rollers while the AMIR compaction involves single roller compaction. Thereafter, pertinent, and relevant measurements such as the field permeability using the NCAT permeameter are taken, and field cores were transported to the laboratory for compaction and density determinations.

The laboratory measurements involve the use of the Superpave gyratory compaction (SGC) method to reproduce samples with similar volumetric characteristics to the field cores using the loose mix samples taken from the field. Thereafter, relevant and applicable measurements such as density and permeability, strength using the indirect tensile strength as a measure are made in order to ascertain relevant parameters and

important factors that could be used to better assess the quality control of finished asphalt concrete pavements.

Figure 3-1 Research Plan

3.1 Project Site Selection

Project site selection was coordinated by the Ministry of Transportation (MTO), Eastern Regional Office which is the supervising agency for all construction projects used in this thesis, the contractor R.W. Tomlinson Ltd. and Carleton University. Project sites include typical road sections under contract and some in-house or local facility trials. Figure 3-2 shows the approximate locations of the selected sites under the jurisdiction of the MTO Eastern Regional Office.

Figure 3-2 Locations of Trial Sites in Ontario Eastern Region

There are ten project locations used in this study. Seven were contractor paved road sections of MTO contracts. For the remaining three, two projects Site 1 and Site 9 were trials (paving of road sections/parking lots) in the contractor's yard while the last project Site 10 was a test road section that was constructed for the purpose of testing different types (vibratory train, oscillatory train and the AMIR) of field compaction equipment. It

is worthy to mention that at all the sites except Site 9; achieving the agency (MTO) set minimum compaction level (density) was the target of the paving operations. Essentially, compaction was controlled for all the test sections except Site 9. In Site 9, three test sections with a varied number of passes for the vibratory train and AMIR were used to study the effect of compaction on the permeability of asphalt concrete. Table 3-1 shows the selected project sections used in this study.

Table 3-1 Project Site Information

<i>Site No.</i>	<i>Site Name</i>	<i>Mix Type</i>	<i>Base Type</i>
1	<i>Yard Trial 1</i>	<i>SP12.5 RAP</i>	<i>Compacted Granular Base</i>
2	<i>1000 Island Parkway</i>	<i>SP 12.5</i>	<i>Compacted Granular Base</i>
3	<i>Highway 417</i>	<i>12.5 FC2</i>	<i>Compacted Granular Base</i>
4	<i>Highway 17</i>	<i>SP 12.5</i>	<i>Compacted Granular Base</i>
5	<i>Highway 16</i>	<i>12.5 FC2 RAP</i>	<i>Compacted Granular Base</i>
6	<i>Highway 520</i>	<i>SP 12.5</i>	<i>Bridge Deck Concrete Base</i>
7	<i>Highway 401</i>	<i>SP 12.5</i>	<i>Bridge Deck Concrete Base</i>
8	<i>Highway 28</i>	<i>SP 12.5</i>	<i>Compacted Granular Base</i>
9	<i>Yard Trial 2</i>	<i>12.5 FC2 RAP</i>	<i>Compacted Granular Base</i>
10	<i>Didsbury Road</i>	<i>12.5 FC2 RAP</i>	<i>Milled Asphalt Road Section</i>

AMIR single roller compaction equipment is an innovative technology that was recently developed to correct the shortcomings of the current rotary steel drum compactor equipment that is popular with the asphalt paving industry. To provide technical and economic data to the paving industry, previous work at Carleton University has studied field compaction using the AMIR and the vibratory train compaction methods such as the work of Chelliah (2019) which included all the projects in Table 3-1 in addition to two more projects which are Highway 7 and Highway 34. The objectives of Chelliah (2019) were mainly to try, evaluate and establish the functionalities and capabilities of the AMIR compactor and compare it with the vibratory steel drum compactor which is the most

common field compaction equipment. The results and conclusions were to guide paving stakeholders on the plausible costs associated with the use of the AMIR compactor and the benefits in terms of economic and pavement performance properties.

Subsequently, the outcome of the various field trials revealed so many issues associated with the impacts of field compaction equipment on the properties of asphalt concrete which the asphalt paving industry was either negligent or ignorant of. Chief among them is the impact of the roller induced cracks on the properties of asphalt concrete such as the water permeability and its implications for asphalt pavement durability. The current quality control and job acceptance specifications are premised on the in-place compacted density of the asphalt mat with no consideration given to the process or procedure of compaction used in paving operations. Furthermore, the methods of field measurement of asphalt pavement water permeability were fraught with many problems. Hence, the primary objectives of this work are to demonstrate and emphasize the impacts of field compaction methods on the quality controls of field compacted asphalt pavement using permeability as a discriminant pavement property for quality control purposes and job acceptance. To achieve this, the vibratory and oscillatory train compactions were compared with the AMIR single roller compaction technology with a focus on water permeability of the compacted asphalt pavements. Paving operational factors such as the base type, influence of steel roller vibrations as well as their interactions and interrelationships were evaluated. Measurements were also referenced to the Superpave compacted specimens using field mixtures for comparative studies and to guide specifications.

Due to the inability of the existing field permeability measurement methods to accurately and reliably measure water permeability, this work further developed a method of measuring field permeability in the field. The newly developed permeability device enables quick water permeability assessments of field compacted asphalt pavements at the time of construction, improves quality control methods and compensation of the contractor as well as ensures more durable roads.

3.2 Field Compaction

The asphalt paving industry has not given much consideration to the impact or effects of various compaction methods on the resulting properties of asphalt pavements. From the foregoing sections, it is now expedient to assess the effects of various compaction technologies on the properties of asphalt pavements with a focus on field permeability as a quality control criterion for job acceptance and payment of contractors in the province of Ontario, Canada. This section presents and discusses the outline of field experimental investigations using various compaction technologies.

3.2.1 Site Preparation

All work items at the various sites used in this study were prepared following the relevant Ontario Provincial Standard Specifications (OPSS). Surface preparations for compacted granular bases, compaction on bridge decks (concrete bases) and milled surfaces followed standard MTO procedures and specifications as may be found in OPSS 310, OPSS 308 and OPSS 313 for asphalt pavement construction and tack coat applications. As mentioned earlier, Yard Trial 2 (Site 9) was used to study specifically the efficiency and economics of vibratory and AMIR compaction methods, hence achieving the target, or set compaction was not the main objective. The first nine projects (Site 1 to

Site 9) contained in Table 3-1 were used for the Case 1 study of the field compaction study while Site 10 only was used in Case 2 of the compaction studies.

3.2.2 Case 1: AMIR Versus Conventional Vibratory Compaction Train

The vibratory steel drum compaction technology has been around for some time now in the asphalt paving industry and is also the most popular asphalt field compactor amongst contractors. Nine of the ten projects used in this study involved only the use of steel roller vibratory compaction train technology and the AMIR single roller compactor. Selected road sections or lanes were dedicatedly compacted by either the conventional steel roller (vibratory plus pneumatic compactor train) or the AMIR (Asphalt Multi-Integrated Roller) roller to achieve target compaction as set by the applicable MTO standards and specifications. As could be seen from Table 3-1, two out of the nine project sites of Case 1 were trials in the yard of a local contractor, i.e. Site 1 and Site 9. Mix types were mainly MTO Superpave 12.5 Nominal Maximum Aggregate Size (NMAS).

Also, to examine if permeability has any relationship with the underlying base types, the field compaction operations were tested on compacted granular bases, milled asphalt concrete and on the bridge deck concrete surfaces for overlay paving of asphalt concrete. Applicable standards and specifications prohibit operating the steel drum roller in vibratory or oscillatory modes when compacting asphalt concrete laid on bridge decks. Thus, achieving set minimum compaction for asphalt concrete laid on a bridge deck concrete are usually difficult for contractors leaving the compacted surface vulnerable to distresses associated with less optimum compaction as well as highly permeable surfaces. Furthermore, highly permeable asphalt concrete resulting from inadequate compaction could potentially allow the permeation and transportation of harmful chemical species that

could harm the surrounding environment and infrastructures (Abd El Halim et al., 2009). De-icing salts used for snow removal and other contaminants from other sources contain harmful chemical species that could corrode steel members, attack concrete installations in bridges and other related infrastructures. Transportation of contaminants through porous media such as asphalt concrete to surrounding water bodies could alter the chemical buffer systems which may be disastrous to aquatic lives.

As hinted earlier in this section, at Site 1 to Site 8, the compacted pavement sections using the vibratory train and the AMIR single roller compaction were used to achieve compaction based on MTO's specifications and standards. Site number 9, however, was of special interest because it directly highlights the efficiency and economics of field compaction and the resulting properties of asphalt pavements by dividing the section into three subsections based on the number of compactor (roller) passes during compaction according to Figure 3-3. For each roller pass of the AMIR compactor, the vibratory steel drum train made three passes counted as the static mode breakdown, pneumatic or intermediate compaction and vibratory finish mode compaction. Target density was monitored using the nuclear gauge for all sites except site 9 and field permeability was measured with an NCAT permeameter per the applicable guidelines (Gilson, 2013). The information relating to the density, relative density, air voids, indirect tensile strength, the base types, and the roller types were recorded.

	Section 1	Section 2	Section 3	
	4x3-passes	6x3-passes	8x3-passes	Steel Vibratory Roller
AMIR	4-passes	6-passes	8-passes	AMIR

Figure 3-3 The Test Plan and Sections of Site 9

3.2.3 Case 2: AMIR, Conventional Vibratory Steel Drum, and HAMM

Oscillatory Steel Drum Compaction Trains

The relationship between field compaction and permeability was studied using Site 10 test sections compacted by three different types of compactors: AMIR, conventional steel drum (vibratory + pneumatic) train and HAMM oscillatory compactor (oscillatory + pneumatic) train. A 200-meter two-lane road section shown in Figure 3-4 was milled and divided into two lanes with one lane compacted using AMIR while the other lane was further divided into two 100-meter sections each for oscillatory and vibratory compaction trains. For the first 100-meter sub-section of the test section at Site 10; one lane was compacted using the HAMM oscillatory compactor train and while the other lane was compacted using the AMIR single roller compaction. The final pavement structure is shown in Figure 3-4. For the second 100-metre sub-section of the test section at Site 10; one lane was compacted using the vibratory plus pneumatic compactor train while the other lane was compacted using the AMIR single roller compaction. The final pavement

structure is equally shown in Figure 3-4. The original plan was to have four 50-metre sub-sections where the vibratory train compacts the first 50-metre on one side, followed by the oscillatory compaction train on the second 50-metre sub-section for the first 100-metre length on the same side with the vibratory train. This pattern would also be repeated for the remaining 100-metre length while AMIR takes the full length of the 200-metre lane on one side. However, the error of the compaction crew resulted in the arrangement shown in Figure 3-4. Figure 3-5 shows a picture of the oscillatory compactor while Figure 3-6 is the AMIR compactor at work at Site 10.

A nuclear density gauge was used to control for density during compaction to ensure approximately the same level of compaction by the three compaction methods typical of Figure 3-7. Both binder and surface courses were of the same mix type with 12.5 NMA. Field permeability measurements were recorded correspondingly across the pavement width while cores and loose samples were taken for density and laboratory measurements.

Figure 3-4 Test Plan and Sections of Site 10

Figure 3-5 HAMM Oscillatory Compactor at Site 10

Figure 3-6 The AMIR Compactor

Figure 3-7 A Nuclear Density Gauge on AMIR Surface

3.3 Data Collection

This section presents brief descriptions of the methods used in data acquisitions based on field and laboratory testing programmes.

3.3.1 Field Testing

During the various field compaction experiments that involved the use of various rollers, field permeability test using the four-tier (segments) NCAT permeameter was conducted on-site immediately after the paving operation when pavement temperature has cooled down to below 30°C. The test was conducted before the road section was opened to traffic. Test points were randomly selected to eliminate bias for lanes compacted by the different

rollers and across the lane width, i.e. on the outer edge, the middle and the inner edge of the lane. Permeability coefficient is computed according to Equation (2.6) given here as Equation (3.0) as explained in Section 2.3.2 following Gilson Inc. (2013) operating manual. Figure 3-8 shows the field permeability measurements using the NCAT in progress.

$$\text{Equation} \quad k = \frac{aL}{AT} \ln\left(\frac{h_1}{h_2}\right) * t_c \quad (3.0)$$

Figure 3-8 Field Permeability Testing in Progress

However, due to some pertinent observations over the extensive course of field permeability measurements using the NCAT device, permeability was calculated for each applicable tier of the NCAT permeameter. Thereafter, the average permeability value of the tiers is reported as the permeability of the tested point for all field tests conducted at

Site 9 and Site 10. Further discussion of this observation would be discussed in Chapter Four. The reported average permeability value of the tested point is the sum of the permeability of the individual tiers where the test occurred divided by the number of tiers of the NCAT permeameter used in the test. Thereafter, the points tested for field permeability were marked, cores were taken from those points as shown in Figure 3-9 for transportation to the laboratory where volumetric measurements and testing are conducted.

Figure 3-9 Typical Coring across Lane width

3.3.2 Laboratory Testing

Cores recovered from the field as well as cores made in the laboratory were measured and tested for their volumetric properties such as the thickness of the cores, the density, air voids and the indirect tensile strength (ITS). The bulk specific gravity of the cores was measured in accordance with MTO standards LS-262 which equally follows

ASTM D2726 (MTO, 1999 & ASTM, 2017). The bulk specific gravity is calculated following Equation (3.1) as follows;

$$\text{Equation} \quad G_{mb} = \frac{A}{B - C} \quad (3.1)$$

G_{mb} = Bulk density of the asphalt core

A = Weight of specimen in air (g),

B = Weight of saturated surface dry specimen in air (g), and

C = Weight of specimen in water (g)

Equation (3.1) above is valid only if the percent of moisture absorption by the immersed cores during the test is below 2% otherwise other methods of density determination using the vacuum sealing method following ASTM D6752 or AASHTO T331 or the coating method according to ASTM D1188 should be used (ASTM, 2015; AASHTO, 2013). The volumetric properties of all the cores used in this work were determined according to ASTM D2726 (MTO, 1999 & ASTM, 2017). The maximum theoretical density is the density of the samples (cores) assuming zero air void is measured. It is determined in accordance with MTO standards LS-264 (MTO, 2012). The maximum theoretical gravity can be calculated following Equation (3.2) as follows;

$$\text{Equation} \quad G_{mm} = \frac{D - E}{(D - E) - (G - H)} \quad (3.2)$$

Where;

G_{mm} = Maximum theoretical specific gravity

D = Mass of beaker and mixture in air, g

E = Mass of beaker in air, g

G = Mass of beaker plus the mass of asphalt mixture in water, g

H = Mass of beaker in water at test temperature, g .

Thereafter, the percent compaction of the core can then be determined following Equation (3.3) while the determination of the air voids of the compacted core follows Equation (3.4) given below.

$$\text{Equation} \quad \% \text{ Compaction (Comp)} = \frac{G_{mb}}{G_{mm}} \times 100 \quad (3.3)$$

$$\text{Equation} \quad \text{Air Void}(\%) = 100 - \text{Comp} \quad (3.4)$$

Equations (3.3) and (3.4) are the mainstay of the quality control protocols of most highway jurisdictions all over the world by referencing field values to the established benchmarks in the laboratory.

Furthermore, field recovered, and laboratory compacted cores were tested for laboratory permeability. The procedure of laboratory permeability adopted in this research was the Florida test method designated FM 5-565 (Florida DoT, 2004). The Florida test method is a well-known procedure used in the assessment of water permeability of compacted asphalt cores. The apparatus is based on the falling head principle and is used to determine the rate of flow of water through the compacted asphalt core housed in a pressurised rubber cell maintained at the pressure of 68.9 ± 3.4 kPa. Water in a graduated cylinder is allowed to flow through a saturated asphalt sample (core), and the time interval taken for the water level to fall from a given upper mark to a lower mark is recorded. The one-dimensional coefficient of permeability of the asphalt sample can then be determined

following Darcy's law and according to Equation (3.0) as explained in Section 3.3.1 above as well as Section 2.3.2 at 20 degree Celsius standard temperature. Figure 3-10 shows the use of the Florida permeability apparatus also known as the Karol-Warner permeameter for laboratory permeability measurements. Details of the test procedure can be found in the Florida test method FM5-565 (Florida DoT, 2004).

Figure 3-10 Lab. Permeability Test using the Florida (Karol-Warner) Apparatus

Finally, the unconditioned indirect tensile test was used as a characteristic mechanical assessment test to determine the strength of the field compacted Superpave cores. The determination of the indirect tensile strength of the Superpave cores follows MTO test method LS-297 which was adopted from ASTM D6931 (MTO, 2011 and ASTM, 2007). The indirect tensile strength of the cores is computed according to Equation (3.5) given by;

$$\text{Equation} \quad S_t = \frac{2000P}{\pi t D} \quad (3.5)$$

Where:

S_t = Indirect tensile strength (kPa)

P = Maximum applied load (N)

t = Core thickness (mm)

D = Specimen diameter (mm)

Figure 3-11 shows the indirect tensile testing of a sample in the laboratory using the INSTRON series 5583 universal testing machine. The core samples at standard room temperature of 25oC were tested with the INSTRON series 5583 loading frame at a loading rate of 2-inches per minute (approximately 50.8mm per minute).

Figure 3-11 Indirect Tensile Testing of a Core Sample

3.4 Description of Variables and Analysis Approach

This section describes the various variables of the data collected and the method of analyses used in this work.

3.4.1 Case 1: AMIR versus Conventional Vibratory Steel Drum Compaction Train

The various field and laboratory data for this study comprise information from 162 samples from nine different paving projects across Eastern Ontario, Canada. Conventional

compactors (vibratory train compaction) and AMIR were used to compact various asphalt pavement sections. Seven out of the nine projects were contractors' projects which involved using the conventional vibratory compaction train and AMIR comparatively to achieve the desired compaction level. In one of the projects i.e. Site 9, AMIR and conventional vibratory train compaction were used to compact three different sub-sections of a varying number of passes of the compactors on a compacted granular base.

Following the outcome of the literature review and the crucial effects of asphalt pavement permeability on performance and durability, regression analysis was used to model the interrelationships between the variables as indicated in the research plan of Figure 3-1. The dependent variable is chosen to be the coefficient of permeability (K), while the independent variables include, maximum theoretical specific gravity (G_{mm}), relative compaction ($Comp$), bulk specific gravity (G_{mb}), air voids (V_a), Indirect Tensile strength (ITS), base type (underlain or underlying base type- P_{avt}), number of passes of the roller, thickness, roller or compactor type (Rol). Mix design variables such as the asphalt content (Ac), compaction temperature ($ComTem$), gradation variables such as the percent by mass of dust content ($Dust$), sieve No. 4 (S_4), sieve No. 8 (S_8), reclaimed asphalt content (RAP), void in mineral aggregates (VMA), performance grading (PG) upper temperature (PGh) and lower temperature (PGl) temperatures, as well as *project locations* (*Site 1 to Site 9*) were also considered as independent variables. The base type (P_{avt}) and roller or compactor type (Rol) are dichotomized dummy variables. The conventional compactor is the reference group for the roller type coded "0", while the AMIR compactor is the comparison group for the roller type coded "1". Similarly, the compacted granular bases are coded as "0" for the reference group and "1" for the bridge deck and milled bases

for the comparison group. Interactions between the independent variables were also evaluated to establish any interrelationships between the variables.

3.4.2 Case 2: AMIR, Conventional Vibratory Steel Drum, and HAMM

Oscillatory Compaction

As mentioned in section 3.2.3 and illustrated in Figure 3-4; the vibratory train, the oscillatory train compactors which are the usual asphalt field compactors available to the paving industry were compared with the AMIR compactor in Site 10. This was purposely carried out to determine the effects of the different compactors on the end-result properties of asphalt concrete in order to provide data and information to guide relevant stakeholders on the quality control and job acceptance criteria. Field permeability was measured using the NCAT permeameter across the width of road sub-sections compacted by various compactors as described earlier. Thereafter, cores were extracted from the points where field permeability was carried and moved to the laboratories for further volumetric measurements and permeability testing using the Florida laboratory permeability device. Also, loose samples were taken from the field to the laboratory where cores were made from them. Thereafter, a statistical study of differences between the compacted sections was made based on compaction and permeability values.

Chapter 4: Field Permeability Measurement and the Development of Carleton Permeability Device

This chapter would discuss the field permeability measurement of asphalt concrete pavements. One of the outcomes of the literature review suggests that the NCAT permeameter is the most common device in the measurement of asphalt concrete pavement. Hence field permeability measurements in this work as outlined in Chapter Three were mainly made using the NCAT device. This chapter would present measurements, results using the most common permeameter (the NCAT permeameter) as well as present the data and observations pertaining to its use especially when measuring multiple points as well as comparing two pavement systems compacted by two or more different compactors. Specifically, the tier system of NCAT permeability is discussed and the associated issues in computing permeability values. Owing to the associated issues with the use of the NCAT device in measuring asphalt pavement permeability, an alternative and improved method of measuring permeability was conceived to correct for the deficiencies of the current device (NCAT). This chapter would introduce and discuss the sensor system used in tracking water level changes. It also presents the methodology and formulations used in the development of the new permeability measuring device termed the Carleton Permeability Device.

4.1 Tier Pattern of NCAT Permeability of Different Roller Compacted Pavements

NCAT permeameter and its use in the measurement and assessment of permeability of asphalt concrete have been widely reported in the literature. The permeameter is a stacked cylindrical column of different diameters (cross-sectional areas) segmented into

three or four tiers. Each tier has a uniform cross-sectional area. The segmentation is believed to aid quick assessment of drainage rate or level of the tested pavement points in relation to other points. However, what is usually not reported in the literature is how the permeability values were measured and calculated in relation to other tested points. Also, it is not usually specified which tier the reported permeability values were measured. The operating manual from the manufacturer of the device Gilson Inc. was not specific on this issue either. The manual only mentioned of filling the device at a steady-state and selecting a tier for recording the rate of flow where the rate of fall is slow enough for accurate observation but fast enough for timely completion of the test. Test time varies depending on the tested surface, but the manufacturer recommended a test time not exceeding five minutes (Gilson Inc. 2013).

However, the manual did not state or recommend what should be done if, during the testing time, the water level falls into a succeeding tier. A modified version of the NCAT device was developed by Worcester Polytechnic Institute (WPI) to improve leak-free interfaces by Mallick et al. (2003). In the testing procedure according to Mallick et al. (2003), the device was filled to a specific mark and the drop of water is noted for 60 seconds. The time to drop 2.54cm or 5cm was noted for a highly permeable surface. The lack of specific test procedures and the reported observation time suggest that the reported permeability values may not necessarily be representative permeability values and the testing procedures are not uniform across tested samples or test points during the tests. Figure 4-1 shows the NCAT permeameter with four and three tiers (segments) while Table 4-1 shows the tier areas and the height marks for the NCAT permeameter with four tiers.

Figure 4-1 Four-Tier (a) and Three-Tier (b) NCAT Permeameters

Table 4-1 NCAT Permeameter Tier Properties

<i>Tier No.</i>	<i>Upper Mark (cm)</i>	<i>Lower Mark (cm)</i>	<i>Cross-Sectional Area (cm²)</i>
<i>1</i>	<i>66.5</i>	<i>51</i>	<i>2.85</i>
<i>2</i>	<i>51</i>	<i>35</i>	<i>15.52</i>
<i>3</i>	<i>35</i>	<i>18</i>	<i>38.32</i>
<i>4</i>	<i>18</i>	<i>0</i>	<i>167.53</i>

In the course of the extensive field measurements of asphalt pavement permeability using the NCAT permeameter in this study, it was observed that using the NCAT permeameter for pavements compacted by the AMIR and conventional compactors exhibit a pattern over the testing time. For the field permeability test in this work, the device is mounted to the tested surface with a plumber putty or a sealing membrane (silicone sealant) between the device and the tested surface to offer leak-free interfaces. Thereafter, the device is filled with water and timed as the water level falls from the top mark (tier 1) to the lower mark possibly in lower tiers till the end of the test as may be decided by the operator but not more than five minutes for the want of time. Thereafter, permeability values are calculated for each tier of the permeameter. Figure 4-2 and Figure 4-3 show the tier permeability values for Site 9 and Site 10. Note that in Figure 4-2 and Figure 4-3 below, the AMIR section has no record in the tier 4 permeability because the water could not fall to tier number 4 during the test time. While the AMIR compactor maintained fairly the same permeability values in the three tiers measured; reporting permeability value for tier one could have meant lower permeability values compared to tier two and three for the conventional compaction in Figure 4-2. For Figure 4-3, choosing to report the tier two permeability values would mean reporting the least permeability values compared to other tiers for the vibratory train and the oscillatory train compactors. While reporting tier 3 permeability for the AMIR compactor would have meant higher permeability compared to tier one and two.

Figure 4-2 Field Permeability Trend of NCAT Permeameter Tiers for the Two Types of Compactors (Site 9)

Figure 4-3 Field Permeability Trend of NCAT Permeameter Tiers for the Three Types of Compactors (Site 10)

From the figures above, it is clearly evident that the NCAT tier permeability values are different as well as the tier pattern for sections compacted by two different compaction technologies. Therefore, the tier permeability values of the NCAT device should be given serious considerations when computing the permeability of the test point. Thus, it makes better sense to measure permeability tier-by-tier under a specific time duration and report the average permeability value for the tested point. This provides a more representative and uniform assessment of the tested points and eliminating bias during testing in relation to other tested points or samples. The variability among the different tiers of the NCAT permeameter result from the void structure of the compacted surface and the relative saturation of the test points as the absolute saturation could potentially be impossible, especially in the field. Another possible explanation is the level of heterogeneity of the conventional compacted section compared to the AMIR compacted sections considering that field flow through the pavement in the field is multi-dimensional and pavement structure is heterogeneous. The rate of the falling head of water both in the field and in the laboratory is reported to slow down with the test progression over time. Thus, decreasing permeability values as the test time progresses (Kanitpong et al., 2001; Menard & Croveti, 2006).

Furthermore, Figure 4-4 presents the ratios of tier permeability to the succeeding tiers two and three for the AMIR compactor and the conventional vibratory steel drum compactor. As noted in the previous paragraphs, when permeability tests are initiated with the NCAT permeameter, the drainage rate or the falling head of water for the first tier is usually the highest as well as the computed permeability coefficient compared to the

Figure 4-4 NCAT Tier Permeability Ratios of Roller Types

succeeding tiers. Therefore, it is expected that the permeability ratio of tier one to other succeeding tiers (tier 2 or tier 3) should be greater than 1.0. However, the ratios from Figure 4-4 indicates that while water level falls as the test progresses, permeability appears to be higher for pavements compacted with conventional compactors. The opposite is the case with the AMIR compactor indicating the anomalous void structure of the conventional steel drum compacted asphalt pavements.

As observed earlier in Chapter Two, the current system of measuring permeability is grossly manual and is prone to error. Record and bookkeeping could be extremely difficult when highly permeable surfaces are being tested with the NCAT system as the water has barely drained out before timing is initiated. Also, as noted in Section 2.3.2 of Chapter Two, the difficulty in maintaining or achieving a leak-free device-pavement

interface during tests usually renders test results unreliable warranting costly repeats of the test. When a successful test is managed to be conducted leak-free, the recorded information could easily be lost or damaged as well as the current system does not allow alternative data acquisition and storage system for backup. More so, the material which the permeameter was made of is so fragile warranting several costly replacements. Most importantly, a more accurate system with good repeatability of results to enhance direct field measurement and assessment of asphalt pavement permeability is needed to aid contractors and supervising agencies to quantify pavement propensity to distresses associated with the intrusion of water and oxidation. To achieve this, a system that can track and record a complete and continuous history of flow or head changes during test time is required to aid automatic real-time data acquisition eliminating some of the drawbacks of the current system in use. Therefore, an alternative system that utilises an electronic sensor system was conceived after due considerations with respect to cost, safety, durability, and portability to make good for the shortcomings of the existing field permeability measurements.

4.2 The eTape Sensor System for the Proposed Carleton Permeability Device

Following the shortcomings of the NCAT permeameter as discussed in Chapter Two and highlighted in Section 4.1; the development of the new Carleton Permeability Device (CPD) envisages and requires the use of a water level sensor because the new permeameter would be based on the falling head framework given the advantages outlined earlier. The sensor is required to track the falling water level over time. The data generated could then be transmitted and stored electronically in order to eliminate manual data acquisitions and errors in booking as mentioned earlier. The factors that were given

consideration as a result of the outcomes of the literature review were cost, reliability, repeatability, durability, and ease of use. After these considerations, Milone Tech. eTape continuous fluid level sensor was chosen to be used in the new device development as an affordable, over-the-shelf solution with a simple design and straightforward operation.

According to Milone Technologies Inc.; the eTape liquid level sensor is a solid-state sensor that makes use of printed electronics housed in a very thin tape against moving mechanical floats to measure fluid levels. The eTape's envelope (tape) senses and measures water level using hydrostatic pressure (compression) of the liquid the sensor is immersed in. This is possible given that the pressure (of any liquid) varies with depth. Therefore, the sensor measures liquid levels using electronic inversion techniques by employing the hydrostatic pressure of the liquid in which it is immersed to determine the raw liquid level over time. The instantaneous raw liquid level is output by the sensor as the electrical resistance of the tape in Ohm (Ω), which changes with the change of liquid pressure (liquid level). Table 4-2 shows the physical characteristics and specifications of the eTape sensor selected for sensing the water level for the proposed CPD while Figure 4-5 shows the variation of resistance with the water level in inches for eTape model-PN 12110215TC-12 with maximum power and voltage ratings of 0.5Watts and 10Volts respectively (Milone, 2019).

Table 4-2 Milone PN 12110215TC-12 eTape Continuous Fluid Sensor (Milone, 2019)

<i>Sensor Length</i>	<i>14.2"(361mm)</i>	<i>Width</i>	<i>1.0" (25.4mm)</i>
<i>Thickness</i>	<i>.015"(0.381mm)</i>	<i>Resistance Gradient</i>	<i>150Ω / inch (60Ω / cm)</i>
<i>Active Sensor Length</i>	<i>12.4"(315mm)</i>	<i>Substrate</i>	<i>Polyethylene Terephthalate (PET)</i>
<i>Sensor Output</i>	<i>400-2000Ω, ± 20%</i>	<i>Actuation Depth</i>	<i>Nominal 1 inch (25.4 mm)</i>
<i>Resolution</i>	<i>0.01 inch (0.25 mm)</i>	<i>Temperature Range</i>	<i>15°F - 140°F (-9°C - 65°C)</i>

Figure 4-5 eTape Resistance-Water Level Graph (Milone, 2019)

As mentioned earlier, the liquid level output of the sensor is in Ohm (Ω). This is because the eTape is modelled as a variable resistor as shown in Figure 4-5 above. For an eTape with a nominal length of 12 inches, as we have above, each of the sensor's outputs corresponds to the water level along the sensor's length (depth of water in the cylinder or vessel). As can be seen from Figure 4-5, the sensor's output (resistance) is inversely proportional to the level of the liquid. That is, the lower the liquid level; the higher the

resistance, and vice versa. The modelling of the eTape follows the transient theory for a resistor-capacitor circuit. In an RC (resistor-capacitor) circuit, the time it takes to charge or discharge the capacitor is related to the resistor given by Equation (4.0);

$$\text{Equation} \qquad \qquad \qquad \tau = RC \qquad \qquad \qquad (4.0)$$

Where ***R*** is the resistance of the resistor measured in Ohms, ***C*** is the capacitance of the capacitor measured in Farad and ***τ*** is essentially the discharge time of the capacitor (the product of ***RC*** which equals the time constant) measured in seconds.

At any instance; for any capacitor of a given capacitance, the range of values of a variable resistor can be determined by measuring the time for different resistor settings. The time for various measurements by the eTape sensor is then displayed in the debug terminal. Lower values of time result from higher liquid levels which correspond to lower resistance values and higher values of time result from lower liquid levels which correspond to higher resistance values. With the use of a voltage divider circuit or inverting operational amplifiers, resistance values of the eTape sensor can then be converted to corresponding voltage readings. The voltage readings thereafter are further digitised using a coprocessor A/D (analogue/digital) converter. Thus, the water level (volume) can be computed at any given instance (Milone, 2019). Figure 4-6 shows the typical eTape sensor made by Milone Tech. Inc. The black plastic cap at the top of the tape is the voltage divider circuitry.

Figure 4-6 Milone eTape Continuous Fluid Sensor (Milone, 2019)

The eTape fluid level sensor was procured and the electronic connections and display were made with the help of a research assistant. Thereafter, the sensor system was tried in several experimental setups for the possible measurements of the permeability of asphalt concrete samples. The digitized output of the sensor reads 1000 units when the permeameter tube or any container is full and 0 when water is below the least graduated reading (lower end) of the sensor surface or length. Time is measured and recorded in milliseconds (msec). The sensor used in this work has a total graduated nominal length of 12 inches or about 300 mm, although it is possible to employ longer sensors. However, it was observed in various studies and trials that the active length of the sensor is mostly about 11.5 inches. The sensor can be immersed in a given liquid in a container such as a cylinder and held using an improvised hanger (suspension) on the top of a burette, cylinder

or any container. Provision is made through the hanger or suspension through which water could pass to fill up the burette, cylinder or container to any desired level.

A computer programme with a graphical display was developed for MTO as part of this research by a programmer with inputs from this author and other team members to fully automate the operations of the new device (MTO, 2019). The sensor and the coprocessor A/D (analogue/digital) converter are connected using a USB (Universal Serial Bus) to a computer. The computer programme that was already installed on the computer is then opened. Thereafter, the cylinder (container) or device is filled with water to the desired level. The sensor is thereafter inserted into the device. Note that the order of filling the device and insertion of the sensor can be reversed depending on the choice of the operator. The test is initiated (started) and stopped by clicking on the start and stop button of the software interface on the computer screen. Test progression depicting the fall of water in the cylinder could be visualised and intuitive inference about the drainage rate or permeability of the tested medium could be immediately made as the test progresses. The fall of the water level was found to have a fairly linear relationship with time, and the steepness of the slope of the line indicates the water drainage rate of the tested surface. Thus, the steeper the slope, the higher the drainage rate as well as the permeability of the tested surface.

The sensor was installed in the Karol-Warner permeameter (Florida permeameter) and was used to take water level-time measurements in the laboratory. The capability of the sensor to track and record water level changes was very satisfactory and consistent based on laboratory observations. Figure 4-7 shows the picture of the sensor in use in the laboratory and field measurements of water level with respect to time. Following the

success of laboratory test trials, an asphalt road strip was constructed in November 2017 along Didsbury Road, Kanata (Site 10), Ottawa for experimental work to study compaction and permeability using three different compactors as explained in Section 3.2.3. The sensor was tried in the field to measure water level changes while being installed in NCAT permeameter after water containment and sealing techniques have been improved by using improvised and over-the-shelf materials. Results were very satisfactory and indicated that the sensor is very capable of tracking and recording water level changes irrespective of the water drainage rates. Figure 4-8 shows the typical plot water level (volume)-time of the sensor.

Figure 4-7 Sensor Assembly for Laboratory and Field Setups

Figure 4-8 Typical Plot of Water Level -Time of the Sensor Tried in the Field

4.3 Laboratory Tests and Calibrations on Laboratory and Field Cores

Following the outcomes of the various laboratory and field trials and characterizations, the next task to find how the sensor output data could be used to measure permeability directly or indirectly was initiated. Several tests and calibration trials were undertaken in the laboratory. The calibration was to match or scale sensor output data with the graduations of the laboratory permeameter (Karol-Warner) so that permeability values can be calculated. Laboratory compacted samples from field mix and field cores recovered from Site 10 were saturated and tested for laboratory permeabilities using the Karol-Warner (Florida DOT) device while the sensor was installed in the device to track water level fall with time. The essence of saturation is to enable constant and consistent results of permeability values to be obtained by reducing variability in the measured permeability

values among the several test runs within a sample. The core samples were tested for laboratory permeability first according to Florida DOT (2004) without using the sensor. With the asphalt core still in the device's housing, the sensor assembly is installed in the burette (cylinder) of the laboratory permeameter after filling it with water. As the water level falls, time and water level changes data that were automatically acquired by the sensor were saved to the computer in CSV (comma separated values) format.

The above procedures were repeated for all the test samples until the variability in timing between consecutive tests is acceptable for the water level to fall from the top to the end of the active length of the sensor. The nominal length of the sensor as mentioned earlier is 12-inch and has an output reading of about 1000 units as the maximum value corresponding to 77 cm of the Florida Laboratory burette. Similarly, the sensor reads a zero when the water level is 50 cm of the Florida permeameter burette. These showed that the sensor's active length is less than 12-inches as mentioned earlier with the topmost less sensitive to water level changes. Armed with this information, a calibration was made to scale or map the sensor output readings to the burette graduations of the laboratory permeameter to enable comparative studies to be made between the two measuring methods before the sensor could be deployed to field operations. Figure 4-9 shows a typical raw water level-time plots as produced by the sensor for one of the tests, and a normalized water level-time plot of the same sample with 1 being the fullest level and 0 being the empty level based on the sensor's actuation length.

Figure 4-9 Sensor Raw Data and Normalized Water Level-Time Graph

One fundamental assumption which is supported by Figure 4-9 is that the water level-time plot could be approximated by a linear trend line to account for the variation due to water level changes and the degree of saturation of the tested sample. The falling head formula for the estimation of the one-dimensional coefficient of permeability (K) is given by Equation (2.6) as provided previously in Section 2.3.2 presented here as Equation (4.1) given below;

$$\text{Equation} \quad k = \frac{aL}{AT} \ln \left(\frac{h_1}{h_2} \right) * t_c \quad (4.1)$$

Based on the assumption that the water-level-time trend line is linear; using the equation of a straight line given below as Equation (4.2);

Equation
$$y = mx + c \Rightarrow V_t = -St + V_{t_0} = V_{t_0} - St \quad (4.2)$$

Where y is the point any time on the vertical axis which represents the sensor water level V_t , m is the slope of the straight line which corresponds to S , x is the horizontal coordinate corresponding to y at time t , and c is the intercept on the vertical axis when time is zero which corresponds to the water level at the start of the test as produced by the sensor V_{t_0} i.e the maximum water level.

From Figure 4-10, S is the slope of the trend line and it is negative because of the inverse relationship between the water level and the time given as Equation (4.3);

Equation
$$-S = \frac{V_t - V_{t_0}}{t - t_0} \quad (4.3)$$

Figure 4-10 Slope of the Water Level-Time Graph of the Sensor

Where V_{t_o} is the initial or start of the test output reading of the sensor assembly corresponding to the maximum or initial level of water at the time t_o and V_t is the output at any other time t corresponding to the level of water at the time at the final or end of the test as the case may be. Note that V_{t_o} does not necessarily have to be at the fullest level of water and likewise V_t does not have to be at the emptiest level of water depending on the testing condition and how permeable the tested surface is. At the end of the test or at any other time as may be decided by the operator; the time denoted as T_t , is given as Equation (4.4) and it is equal to Equation (4.0);

$$\text{Equation} \quad T_t = \frac{V_{t_o} - V_t}{S} \quad (4.4)$$

Equation (4.4) is based on the assumption of a linear relationship between the output water level of the sensor and time. Also, the test time T_t can be estimated from the slope S irrespective of the level of water in the tube provided the water level is within the sensor range based on this assumption of a linear relationship.

Recall, that the sensor's output represents measures of changes in water level from the top of the sensor's (tape length) to its bottom. Therefore a scaling conversion is required to relate the sensor output reading (water level) to permeameter (device) height changes which may be based on constant cross-sectional area or variable cross-sectional area from the top of the permeameter (highest liquid level) to the ground or tested surface as the water level falls. This enables the establishment of the relationship between the sensor output and the actual height of the device. With this, the actual head of water is known at any point in time and used to calculate the permeability coefficient using the permeability equation. Based on several readings made in the laboratory using the Karol-Warner device of 77cm

height, a conversion relationship from the sensor output to pressure head based on Karol-Warner permeameter is given in *cm* as Equation (4.5);

$$\text{Equation} \quad h = 0.02787V + 49.115 \text{ (cm)} \quad (4.5)$$

When $V = 1000$, then $h_1 = 76.985 \text{ cm}$, when $V = 0 \text{ mV}$, then $h_2 = 49.115 \text{ cm}$ for the sensor length (12-inch designate) used in this experiment. The data that gave rise to this equation is presented in Table B. 1 of Appendix B. Note that as earlier mentioned, the actual sensitive length of the sensor is less than 12-inches. Armed with the above information, several test experiments, trials, and calibrations were made in the laboratory, and based on the active length of the sensor, an equation that is independent of any device with constant cross-section that can be used in any setting but solely based on the sensor length was developed and given by Equation (4.6) in *cm*;

$$\text{Equation} \quad h = 0.02794V + Z \text{ (cm)} \quad (4.6a)$$

Alternatively, Equation (4.6) can be written in inches as;

$$\text{Equation} \quad h = 0.0111V + Z \text{ (inches)} \quad (4.6b)$$

Where h is the height of the device at any instance, V the output reading of the sensor, Z is the device constant which physically represents the distance from the tested surface (ground or sample surfaces) to the least graduated (lower) end of the sensor. The data upon which this calibration is made is given in Table B. 2 of Appendix B.

Essentially, both the permeability coefficient calculated from the head-time slope and the permeability coefficient directly measured based on the actual time can be computed from the sensor measurements. Ideally, therefore, Equations (4.4) and (4.0) are

equal since both equations equal to the time and can be written respectively as Equation (4.7).

$$\text{Equation} \quad \tau = RC = T_t = \frac{V_{t_0} - V_t}{S} = \frac{h_1 - h_2}{S} \quad (4.7)$$

Substituting Equation (4.5) for the height, Equation (4.7) for the time into Equation (4.1) yields Equation (4.8) for the one-dimensional permeability equation for the Karol-Warner device (Florida Device) based on the sensor's raw data and the slope of the linear trend line.

$$\text{Equation} \quad k = \frac{aL}{A \frac{V_{t_0} - V_t}{S}} \ln \left(\frac{0.02787V_{t_0} + 49.115}{0.02787V_t + 49.115} \right) * t_c \quad (4.8)$$

Alternatively, the permeability coefficient can be computed based on the actual time recorded by the sensor as well as by substituting T_M in the permeability equation, where T_M is the actual test time recorded by the sensor. Substituting T_M in place of $\frac{V_{t_0} - V_t}{S}$ in Equations (4.8) given above, yields Equation (4.9);

$$\text{Equation} \quad k = \frac{aL}{AT_M} \ln \left(\frac{0.02787V_{t_0} + 49.115}{0.02787V_t + 49.115} \right) * t_c \quad (4.9)$$

Equations (4.8) and (4.9) are almost the same except for the method of time used in calculating the coefficient of permeability. At the start of the test, using the sensor; $t = 0$, $V_t = V_{t_0} - St = V_{t_0} = V_1$. Similarly, at the end of the test; using the sensor; $t = t$, $V_t = V_{t_0} - St = V_2$. $V_2 = 0$ at any time during the test if water has fallen below the (lower sensing) end of the sensor. Therefore, Equations (4.8) and (4.9) for a Karol-Warner device can be written as shown in Equation (4.10).

$$\text{Equation} \quad k = \frac{aL}{A \frac{V_{t_0}}{S}} \ln \left(1 + \frac{0.02787V_{t_0}}{49.115} \right) * t_c \quad (4.10)$$

For any other device that may not necessarily be transparent and graduated as the current Florida or NCAT permeameters; Equation (4.6) which is based on the length of the sensor tape can be used. Hence, using a device with a known uniform cross-sectional area, test specimen area and thickness; based on 12-inch sensor length, the permeability equation can be computed with Equation (4.11a) in cm/sec or Equation (4.11b) in inch/sec otherwise, an extra input at any instance is needed for the cross-sectional area of the device column to enable computation of permeability coefficient.

$$\text{Equation} \quad k = \frac{aL}{A \frac{V_{t_0}}{S}} \ln \left(\frac{0.02794V_{t_0} + Z}{Z} \right) * t_c \quad (4.11a)$$

$$\text{Equation} \quad k = \frac{aL}{A \frac{V_{t_0}}{S}} \ln \left(\frac{0.0111V_{t_0} + Z}{Z} \right) * t_c \quad (4.11b)$$

As mentioned earlier, Z is the height between the end of the sensor in the device column to the specimen or pavement surface. The temperature correction factor t_c can be approximated by Equation (4.12) in degree Celsius as;

$$\text{Equation} \quad t_c = 2.42 - 0.47566665 \ln(T^\circ C) \quad (4.12)$$

Thus, Equation (4.11a), Equation (4.11b) and Equation (4.12) can be used as an input in the computation of the one-dimensional permeability coefficient and the

temperature correction factors in the analysis software package. Hence the sensor can be used for any or purpose-built device regardless of the shape provided it has a uniform cross-sectional area to avoid the additional requirement of knowing the cross-sectional area of the device at any given time as the water level falls during permeability tests.

4.4 Application of Head-Time Slope to Measurements of Permeability

The current system of measuring field permeability with the NCAT permeameter poses two major challenges in terms of measurements and comparison of permeability values of two or more tested samples in the field; (a) keeping testing conditions the same for all samples i.e. starting water level (upper timing mark) and ending water level (lower timing mark) with respect to time and (b) ambiguity in the calculation of permeability values when the test tier numbers are not the same for the two or more points being tested as discussed in Section 4.1. Permeability testing assumes complete saturation which is potentially impossible in the field and in some cases, the testing time could be unusually long. One advantage of using the sensor system and the developed methodology of measuring permeability is that the water level-time slope enables the extrapolation or interpolation of measurements in a reasonable time to estimate and forecast water level or time; hence permeability values. The water level-time slope also allows the operator to compare two or more test points' permeability values. This can be achieved by maintaining or referencing two head limits (upper and lower marks of the permeameter) of the water level and shifting the head-time line as may be deemed appropriate by the testing agency or the operator as shown in Figure 4-11. Hence, computation and comparison of the permeability of two or more test points can be achieved given two specific upper and lower marks of the permeameter thereby unifying test conditions of the tested points.

Figure 4-11 Conceptual Application of Head-Time Slope Methodology for the Permeability of Two Systems

4.4.1 Comparisons of Permeability Measurements using the Sensor System

This section presents calibration results, application of the head-time slope and comparative measurements of permeability following the developed methodologies using Equations (4.1), (4.8) and (4.9) using the Karol-Warner laboratory (Florida) device. These equations computed permeability coefficients using the slope of the water level-time trend line (Slope) and the actual test time recorded by the sensor (Measured) and comparing them with the direct values measured manually with the laboratory device (Florida Lab.). Various permeability values were measured and calculated for the laboratory compacted samples as well as field cores recovered from the wearing course section of *Site 10* where the three different compaction technologies were used. Table 4-3 shows the outcome of the calibration and verification of the sensor system used on the Karol-Warner device (Florida

Device) to measure laboratory permeability on laboratory compacted cores. The three differently calculated permeability values i.e., the Florida Method (Karol-Warner), the slope and the sensor recorded time agree quite well. Similarly, a plot of permeability values based on the time calculated from the slope of water level-time trend line versus Florida Laboratory permeability and measured laboratory permeability using the sensor's actual recorded time was made to establish the extent of agreements between the three differently measured permeability values based on the line of equality plot. Figure 4-12 indicates that the three differently calculated permeability values agree quite well for the Superpave gyratory compacted (SGC) specimens made from field mix while Figure B. 1 through Figure B. 3 of Appendix B are similar plots for field compacted cores by the three different field compactors. Please observe that in these figures, the Slope and the Measured permeability values are both plotted on the same vertical axis. Thus, either of the three differently measured permeability values can be used interchangeably since they are equivalent to one another thereby enabling uniformity of test results and comparisons. Details of the preceding procedure on field recovered cores are provided in Table B.3 through Table B. 5 of Appendix B.

Table 4-3 Sensor Slope, Sensor Measured and Florida Permeability for SGC Cores

<i>Air Voids (%)</i>	<i>Sensor Slope Permeability (cm/secs)</i>	<i>Florida Lab. Permeability (cm/secs)</i>	<i>Measured Sensor Permeability (cm/secs)</i>
3.54	0.00E-00	0.00E-00	0.00E-00
3.97	0.00E-00	0.00E-00	0.00E-00
4.13	0.00E-00	0.00E-00	0.00E-00
4.45	0.00E-00	0.00E-00	0.00E-00
4.45	0.00E-00	5.47E-06	0.00E-00
4.67	5.43E-05	5.69E-05	5.43E-05
4.67	5.31E-05	5.40E-05	5.31E-05
6.01	0.00E-00	0.00E-00	0.00E-00

6.01	0.00E-00	8.10E-06	0.00E-00
6.63	2.00E-04	2.05E-04	2.20E-04
6.63	2.00E-04	1.87E-04	2.07E-04
6.52	4.58E-04	4.51E-04	4.61E-04
6.52	4.47E-04	4.50E-04	4.62E-04
6.97	2.26E-04	2.35E-04	2.41E-04
6.97	1.82E-04	2.02E-04	1.82E-04
9.22	3.74E-04	3.71E-04	3.73E-04
9.22	3.42E-04	3.07E-04	3.58E-04
9.22	2.81E-04	2.77E-04	2.86E-04
9.3	1.04E-03	1.03E-03	1.07E-03
9.3	8.46E-04	8.64E-04	8.96E-04
9.3	7.16E-04	7.28E-04	7.37E-04
9.5	2.56E-03	2.55E-03	2.59E-03
9.5	2.45E-03	2.38E-03	2.48E-03
9.5	2.48E-03	2.38E-03	2.36E-03
9.93	3.45E-04	3.03E-04	3.65E-04
9.93	3.29E-04	3.00E-04	3.47E-04
9.93	3.29E-04	3.01E-04	3.45E-04
9.93	2.96E-04	2.72E-04	3.17E-04
10.1	2.00E-03	2.02E-03	2.03E-03
10.1	1.92E-03	1.93E-03	1.97E-03
10.1	1.86E-03	1.71E-03	1.90E-03

Figure 4-12 Equality Plots of Various Measured Lab. Permeabilities for SGC Cores

4.4.2 Analyses of Variance (ANOVA) of Sensor, Florida, and Measured Lab. Permeabilities

Because of the slight variations observed between the Florida laboratory permeability and the other two permeability values calculated differently, the statistical investigation was employed to check if there are significant differences between the three different permeabilities. The null hypotheses for the equality of means of the three differently computed laboratory permeabilities are equal was tested. Using analysis of variance (ANOVA) test, the variability in the observed measurements between the three permeabilities was evaluated to check if the reported values differ significantly from one

another. The null hypothesis is rejected if the test of equality of means is significant at the set level of significance which of 5% as used in this study. Table 4-4 shows the SPSS 26 summary for all the data for all the three differently computed permeability values i.e. Florida, Slope and the measured. It shows that there is no significant difference between the three differently measured permeability values.

Table 4-4 ANOVA Table for the Three Differently Calculated Permeabilities

<i>Perm. Type</i>	<i>Sum of Squares</i>	<i>df</i>	<i>Mean Square</i>	<i>F</i>	<i>Sig.</i>
<i>Between Groups</i>	8.572E-09	2	4.286E-09	.00632	.994
<i>Within Groups</i>	6.10E-05	90	6.784E-07		
<i>Total</i>	6.10E-05	92			

4.5 Device-Pavement Water Leakage Solution

Maintaining leak-free interfaces and fluid containment is one of the major deficiencies of most field permeameters that have not been usually reported in the literature (Li et al., 2013; Kayhanian et al., 2012). Experiences using the field permeameters showed that the fluid leakage at the device-pavement interfaces could be so severe that the test results have to be rejected and the tests repeated thereby increasing the testing time and costs associated with the testing. Several caulking sealants and polymer membranes were assessed both in the field and the laboratory environments with different weight combinations to apply pressure to contain fluid and prevent leakages at the device-pavement interfaces. Although the NCAT permeameter comes with a plumber putty which is moulded around the device open area in the base that is attached to the pavement.

However, maintaining a consistent device area is difficult to achieve using the plumber's putty. Also, in frigid weather, the putty is not mouldable and very brittle. To solve this leakage problem, materials evaluated include bitumen mat, over-the-shelf plumber gaskets, silicone sealants, improvised polymer foams, closed-cell neoprene, and urethane membranes. Figure 4-13 shows Dow Corning multi-purpose silicone sealant that was used to improve device-pavement fluid containment for the NCAT device. Figure 4-14 is the bituminous mat used to study sealing improvement at the device-pavement interfaces while Figure 4-15 shows one of the trials where bitumen mat and sealant used on NCAT device to check their capability in providing leak-free interfaces.

Figure 4-13 Dow Corning Sealant used to Improve Fluid Containment

Figure 4-14 Bituminous Mat with Improved Caulking Material

Figure 4-15 Alternative Sealing Membrane on Old Pavement for the NCAT Device

Based on several sealing assessments conducted, over-the-shelf plumber gaskets as shown in Figure 4-16 worked perfectly in sealing the device-pavement interfaces under the self-weight of the device without requiring additional weight for a device weighing up to 44 kg. However, a manufacturer that could get the right size and dimensions as required by MTO could not be found and the distributor/seller was not ready to release information about the manufacturer. Therefore, the option of using this gasket even though it worked well was suspended.

Figure 4-16 One of the Proprietary Plumber Membranes Tried

Following the over-the-shelf plumber gasket in sealing the device-pavement interfaces were the neoprene and urethane gaskets. Further testing indicated that the urethane and neoprene closed-cell membranes could provide satisfactory sealing of water

from the interfaces on typical asphalt pavement surfaces. However, closed-cell neoprene with 6-inches internal diameter by 8-inches external diameter by 3/8-inch thickness was selected for the new device with an additional surcharge weight of 30kg to provide sufficient sealing to the device-pavement interfaces. Figure 4-17 shows the neoprene membrane used to seal off the device-pavement interface for the proposed new device.

Figure 4-17 Neoprene Sealing Membrane on the Prototype Device

4.6 Design Considerations and Proposed Development for the Prototype Device

Several factors such as the device's uniformity of tester area and material selection were given consideration with some inputs from the Ministry of Transportation Ontario (MTO) in developing the prototype for the new permeability device and its method of measurements. First, asphalt core samples have a 6-inches diameter under the current Superpave system. Hence devices such as the laboratory Karol-Warner device and the

NCAT device have a tester size of 6-inches as well. As noted earlier, another important issue with the NCAT permeameter is that the plexiglass material used in making the device is highly fragile. The material breaks easily and warrants frequent and costly replacements. More so, the device has to be transparent all the time to enable the operator to take readings. This, however, becomes difficult with time due to the use and ageing of the plexiglass making it to be too opaque therefore difficult to take readings during tests because the operator must see through the device to observe water level fall with time. However, with the sensor and its methodology of measurement, the proposed new device tubing does not necessarily have to be transparent. Hence, more durable, and opaque materials such as metallic materials could be used with the sensor. The operator does not have to see the water level fall. The user simply keeps a tab of the test progression with the graphical display on the computer screen.

Furthermore, usually with the NCAT system, as the device is being filled with water, water immediately starts saturating the pavement. In some highly permeable surfaces, getting the device full before timing starts could be difficult and, in some cases, taking readings is practically impossible. This is particularly important because the degree of saturation of the pavement during the testing could seriously affect the results. Hence, a lock valve option was introduced to lock the water from reaching the pavement until the device is full and ready for testing. This allows the testing criteria to be maintained for all specimens. In the end, two prototypes for the device were made and proposed. Initially, one with an internal cylinder diameter of 3-inch (77.5mm) with valve lock and the second with the 2-inch (52mm) cylinder diameter with the option of valve lock. The detailed physical information of the two prototypes is shown in Table 4-5. Figure 4-18 is the device

prototype 1 while Figure 4-19 is the device prototype 2 showing the neoprene membranes and the lock valve option cylinder.

Table 4-5 New Device Prototype Sizing Proposed

<i>New Device Prototype Sizing Information</i>		
	<i>Prototype 1</i>	<i>Prototype 2</i>
<i>Total Instrument Height</i>	<i>105cm</i>	<i>66.5cm</i>
<i>Cylinder Internal Diameter</i>	<i>7.75cm</i>	<i>5.2cm</i>
<i>Base Disc Diameter</i>	<i>35cm</i>	<i>23cm</i>
<i>Total Device Weight</i>	<i>44kg</i>	<i>15.5kg</i>
<i>Base Disc Thickness</i>	<i>5cm</i>	<i>5cm</i>
<i>With Control Valve Option</i>	<i>Yes</i>	<i>Yes</i>

Figure 4-18 Prototype 1 Device

Figure 4-19 Prototype 2 with valve lock option and the Neoprene Membranes

Therefore, for the sake of maintaining conditions for testing Superpave cores, it is required that the proposed new device's area be circular with a diameter of 6-inches to match the laboratory specimen size. Also, the volume of water required for each test was considered. Hence, the 2-inches (5.2cm) diameter prototype 1 which has the height and tester area made to match that of the NCAT system was considered for further considerations and use. The height, tester area and cross-sectional area of the device are options that the supervising agency may decide on based on specific choice and purpose with respect to the observations of Harris et al. (2011) and Hall (2004). These would depend on the relationship envisaged between laboratory and field specimens, and whether tester uniformity is an important criterion or not based on the. An option to automatically

fill up the device is included based on the sensor readings of the water level using a water pump. The pump is powered by a rechargeable battery pack. Also, to enhance capacity and speed, an option to have multiple sensors and devices was considered for future development. Figure 4-20 is the conceptual diagram of the design of the Carleton Permeability Device while Figure 4-21 shows the trial test using the 3-inch prototype and the pump on the asphalt slab with the components.

Figure 4-20 Conceptual Design of the Carleton Permeability Device (MTO, 2019)

Figure 4-21 Trial Testing on asphalt Slab using the pump

4.7 Field Applications and Operations of the New Permeability Device

The section presents and discusses the application and the use of the newly developed permeability device to measure field permeability values. The new device being proposed is the prototype 1 which consists of a circular metallic disc of 23cm diameter, a 2-inch internal diameter cylinder made with steel and a total height of 66.5cm as presented earlier in the previous section as contained in Table 4-5. Figure 4-22 shows the schematic diagram of the prototype with the sensor mounted on top and its length extending down into the cylindrical column of the device. The steel cylinder provides a sturdy and stronger material as against the highly fragile Plexiglas used in the NCAT permeameter. Therefore, no need for frequent costly replacements.

Figure 4-22 Field Application of the Sensor System and the New Device

Furthermore, the sensor system when combined with the steel tester cylinder eliminates the need to visually track water level and to manually take readings during measurements. Figure 4-23 shows the picture of the new permeability device (prototype 1 without lock valve) in use in the field.

Figure 4-23 The New Permeability Device in Use in the Field

4.7.1 Operations of the Carleton Permeability Device and Data Acquisition

To use the new Carleton Permeability Device in the field, the base of the device is first cleaned and is devoid of rust and debris. Thereafter, the adhesive surface side part of the closed-cell neoprene membrane is glued to the device base that faces the tested surface for the tester-pavement interface sealing. The neoprene membrane can be used for several tests provided it can sufficiently provide sealing. The device with the membrane glued to its base is simply put at the point on the pavement surface where permeability is to be evaluated. The sensor is inserted into the top of the steel cylinder and connected to the

microcontroller (A/D converter) which is in turn connected to the appropriate computer USB port. The permeability data acquisition application (PDA) software which was developed as part of the work for MTO as explained earlier is opened (launched) on the computer. Water is then introduced into the device cylinder column and filled to the top level close to the sensor mount to avoid spillage and protect the divider electronics against flooding which could damage the electronics. Permeability test is initiated with the click of the start icon/button of the PDA on the desktop. If the connections are properly made, the data acquisition application for a typical test run would appear as shown in Figure 4-24 below over time. Note that the order of filling the device with water and the introduction of the sensor is not specific, they can always be interchanged depending on the operator.

Figure 4-24 Data Acquisition Application Interface

At the lower right corner of the data acquisition figure above is the pump option menu for filling up the device during testing operations. When using the pump to fill up the device against manual fill up, this option allows the sensor and the associated electronics to automatically control the speed of the pump and the fill flow rate based on the water level in the device as monitored by the sensor. At the lower left-hand corner of Figure 4-24 above is where the test ID can be inputted thus doing away with manual bookkeeping and its associated problems. The test information is automatically stored in a dedicated folder on the desktop for onward processing in a comma-separated values (CSV) format as shown in Table 4-6 below. The first column of the data is the test progression

time in seconds while the second column is the water level raw data and the lower right corner is the test ID, the test time and date.

Table 4-6 Test Stored Information in CSV Format

	A	B	C
1	Tme (msec)	Water Level (units)	
2	0	0	
3	100	70	
4	201	72	
5	299	162	
6	400	179	
7	500	272	
8	601	295	
9	701	302	
10	801	334	
11	901	335	
12	1001	365	
13	1101	367	
14	1201	406	
15	1301	424	
16	1401	444	
17	1501	485	
18	1601	491	
19	1701	507	
20	1801	507	
			A1R4-T27-1_14h30m_3-2-2018

4.7.2 Processing Device Test Results

The stored test data in CSV format from the folder can be further processed with the Permeability Data Processor (PDP) application as shown in Figure 4-25 below.

Figure 4-25 Permeability Data Application Processor Application Interface

The name provides for the labelling of the test ID. This allows operators to label name the tested points based on project identifiers such as name, location, chainages, lot or subplot, compaction type or method and any reference that may be of interest to the operator or testing agency. Colour delineation is provided for blue, green, and red to make differences in plotting results based on the specific interest of the operating agency. Figure 4-26 shows the calibration submenu of the Permeability Data Processor for the device. Please, note that the values shown below are simply for illustration and do not represent real calibration values for any equipment.

Calibration Menu (v2.0)

Calibration parameters:

T = 24 (C) Pavement temperature

d = 4.5 (cm) Diameter of stand pipe

D = 15 (cm) Diameter of sample

L = 5 (cm) Pavement/Sample thickness

H = 63.5 (cm) Apparatus height

Save

Figure 4-26 The Calibration Submenu of the Permeability Processor

As mentioned earlier, the sensor system and its methodology of measuring permeability electronically are universal provided that the test method is falling head and a uniform tester cylinder cross-section are used otherwise, the cross-sectional area needs to be known at any instance to compute volume. That does not, in fact, invalidate its use in a segmented tester device like the NCAT device. However, the calibration for each segment or tie is needed which could be a bit complex depending on the number of segments or the relationship of the device height and its cross-sectional area. Thereafter, the plot button is used to produce the slope and calculate permeability as shown in Figure 4-27.

Figure 4-27 Sample Plot and Permeability Result from the Permeability Data Processor

Chapter 5: Results, Analyses of Compaction and Permeability Studies

This chapter presents and discusses the results and analyses of the research performed as outlined in Chapter 3. These comprise the various field compaction trials involving the vibratory train, oscillatory train compaction technologies and the innovative AMIR single roller compactor. Results of laboratory measurements of compaction and permeability will also be discussed.

5.1 Field Compaction, Permeability, and Influential Factors

This section presents the results of Case 1 of the field testing involving different compaction and permeability studies for the nine project locations (*Site 1 to Site 9*) where the vibratory compaction train and AMIR single roller compactor were used to compact different asphalt road sections as planned and shown in Figure 3-1. This was aimed at achieving the first objective of the work which is to identify and evaluate the effects of compaction technologies available to the asphalt industry on key asphalt pavement attributes related field compaction. First, various results of the field compaction studies are presented for the two types of compactors used to compact various sections of asphalt pavements. Secondly, statistical analyses using the analyses of variance (ANOVA), ordinary least square regression and the mixed modelling approach to evaluate associations, differences, and relationships between various variables.

Table 5-1 shows the summary of the variables recorded from the various field compaction trials for both the AMIR and the vibratory steel drum compactors. Table 5-2 shows the descriptive statistics of the most important variables split by compaction method. Given that the field compaction was monitored using the nuclear gauge to keep the

compacted sections relatively at the same compaction level (except Site 9), it was not surprising to see that the compaction level of the two roller sections was reasonably the same. Although, experience has shown that the nuclear gauge is not an accurate measure of field compaction level, the asphalt paving industry has found it useful in monitoring density evolution during compaction. This is especially so for the conventional compaction methods as their measurements correlate well with the laboratory measurements. The reliability of these measurements depends on the calibration, setting, and experience of the operator. AMIR compacted sections still maintained lower permeability values as well as less variability in permeability compared to the vibratory steel drum compactors. Note that the mean and standard deviation were not calculated for dummy variables such as the *Pavt* and *Rol*.

Table 5-1 Summary of Various Variables Collected from the Nine Project Locations

<i>Variable</i>	<i>N</i>	<i>Mean</i>	<i>Std Deviation</i>	<i>Minimum</i>	<i>Maximum</i>
<i>K (10⁻³ cm/sec)</i>	162	4.28	7.00	0.005	45.3
<i>Comp (%)</i>	162	92.35	2.41	86.18	98.23
<i>Va (%)</i>	162	7.65	2.41	1.77	13.82
<i>Gmm</i>	162	2.53	0.049	2.38	2.66
<i>Gmb</i>	162	2.34	0.055	2.17	2.48
<i>ITS (kPa)</i>	132	267.23	186.37	42.25	1024.21
<i>Pavt (granular base = 0; concrete base = 1)</i>	162	-	-	0	1
<i>Rol (conventional = 0; AMIR = 1)</i>	162	-	-	0	1
<i>Pass</i>	162	15.84	7.13	4	24
<i>Thick (mm)</i>	162	52.43	7.39	42	95

Table 5-2 Important Variable Descriptive Statistics

<i>Compaction Type</i>	<i>Descriptive Statistics</i>	<i>Relative Compaction (%)</i>	<i>Va (%)</i>	<i>K (10⁻³ cm/sec)</i>	<i>ITS (kPa)</i>
<i>AMIR</i>	<i>Mean</i>	92.60	7.40	3.97	273.71
	<i>Std Dev</i>	2.89	2.89	5.47	233.40
<i>Vibratory</i>	<i>Mean</i>	92.11	7.89	4.49	263.15
	<i>Std Dev</i>	1.92	1.92	7.90	150.97

Due to operational constraints, AMIR single roller compactor was used side-by-side with the vibratory steel drum compaction train on five projects. The common projects include Site 1, Site 2, Site 7, Site 8, and Site 9. Figure 5-1 is the variability (box) plot of the compaction level while Figure 5-2 is the boxplot of the air voids of the cores extracted from the various sections compacted split by the compactor type for the nine different projects. Although the AMIR roller-compacted section in Site 1 has a higher mean compaction level and lower mean air voids level compared to the vibratory train compacted section, AMIR compacted section of Site 1 has higher variability compared to the vibratory train compacted section. This is not unexpected since the AMIR roller is a novel technology that operators had no prior experience of its use. Another factor that may have played a role is the experience of using the density gauge to monitor density evolution during compaction for the AMIR compacted section.

Figure 5-1 Compaction Boxplot by Compactor Type for Various Sites

Figure 5-2 Air Voids Boxplot by Compactor Type for Various Sites

Figure 5-3 is the boxplot of the ITS by the compactor type for the various locations. ITS was used as a measure of strength indicator and AMIR compacted sections have higher ITS values compared to the vibratory compacted sections. Note that the ITS was not measured in Site 9. Figure 5-4 is the boxplot of the field permeability coefficients measured with the NCAT device by the compactor type for the nine project sites. Apart from Site 1 where experience probably may have influenced the performance of the AMIR compactor in having higher permeability values compared to the vibratory compaction train, the AMIR compactor had lower permeability values compared to the vibratory compacted sections.

Figure 5-3 ITS Boxplot by Compactor Type for Various Sites

Figure 5-4 Permeability Coefficient Boxplot by Compactor Type for Various Sites

As mentioned previously, the field compaction trials using the AMIR and the vibratory train compactors were used to compact asphalt concrete sections laid on compacted granular surfaces and the more rigid bridge deck concrete surfaces where the steel drum roller could not be used in the vibratory mode. Figure 5-5 is the boxplot of the compaction level while Figure 5-6 is the air voids of the cores extracted from various project sites split by the compactor type and the type of base upon which the asphalt concrete was laid on. The base type *Pavt* is a dichotomised (dummy) variable with 0 for the granular base type and 1 for the more rigid bridge deck concrete base. AMIR single roller-compacted surfaces have a higher compaction level although with higher variability than the vibratory compaction train compacted sections. This high variability could be

attributed to Site 1 which was the first site for the trial where the AMIR process was not fully understood by the operators. Also, asphalt pavement surfaces compacted on compacted granular base have a higher compaction level compared to those compacted on more rigid surfaces like the bridge deck concrete.

Figure 5-5 Compaction Boxplot by Base Type and Roller Type

Furthermore, Figure 5-7 is the boxplot of the indirect tensile strength (ITS) of cores recovered from the sites. Again, AMIR compacted sections have higher strength indicators as measured with ITS compared to the vibratory compacted sections. More so, sections compacted on more rigid bases such as the bridge deck concrete have higher ITS values compared to those compacted on compacted granular bases despite these sections having lesser compaction values.

Figure 5-6 Air Voids Boxplot by Base Type and Roller Type

From the figure, the sections compacted on more rigid surfaces have higher permeability values compared to those compacted on a more flexible surface. This is evident because the asphalt concrete sections compacted on a more rigid base have lower compaction levels compared to those compacted on a more rigid surface. Figure 5-9 is the boxplot of the number of compactors passes by compactor and base types. While there is no apparent difference between the number of compactors passes for the surfaces compacted on the two base types, AMIR generally has a lesser number of roller passes compared to the vibratory train compaction method.

Figure 5-7 Indirect Tensile Strength Boxplot by Base Type and Roller Type

Figure 5-8 Permeability Boxplot by Base Type and Roller Type

Figure 5-9 Number of Roller Passes by Base Type and Roller Type

Also recall that for Site 9, specifically, AMIR and the conventional vibratory steel drum compactor were used to study the optimum compaction parameters based on the number of roller passes of the two compaction systems. Table 5-3 shows the section information and compaction parameters of Site 9. Recall that the roller pass count of the conventional vibratory drum compactor included the breakdown, intermediate and finish counts of the various modes of compaction. Hence each count of the AMIR roller pass equates three counts of the vibratory roller pass.

Table 5-3 Compaction Studies of the Two Roller System for Site 9 Optimum Compaction Studies

<i>Compactor</i>		<i>Nos. of Roller</i>		
<i>Type</i>	<i>Section</i>	<i>Passes</i>	<i>Permeability (cm/sec)</i>	<i>Compaction (%)</i>
AMIR	1	4	4.77E-03	89.04
	2	6	2.86E-03	89.93
	3	8	1.73E-03	91.82
Vibratory	1	12	8.28E-03	89.57
	2	18	8.83E-03	90.90
	3	24	3.39E-03	92.74

Figure 5-10 is the compaction boxplot for the AMIR and the vibratory train compacted sections of Site 9 while Figure 5-11 is the air voids boxplot for the AMIR and the vibratory train compacted sections of Site 9. Figure 5-12 shows the permeability boxplot for the AMIR and the vibratory train compacted sections of Site 9. A1 is the AMIR compacted section with four passes corresponding to V1 section of the vibratory train compacted section with twelve passes. A2 is the AMIR compacted section with six passes corresponding to V2 section of the vibratory train compacted section with eighteen roller passes. A3 is the AMIR compacted section with eight roller passes corresponding to V3 section of the vibratory train compacted section with twenty-four roller passes. The AMIR roller compacted sections despite having a smaller number of passes produced compacted sections with consistently lower permeability values and spread compared to the conventional vibratory steel drum train compactor even though the compaction level is comparable. Figure 5-13 shows the typical AMIR and the vibratory compacted surfaces in Site 9. The top left-hand side of the picture labelled A-a is the close-up shot of the AMIR surface while the top right-hand side of the picture is the cracked and chalky surface of the steel vibratory compacted surface labelled V-a. The lower end of the picture is a section compacted by the two compaction methods. The left-hand side labelled A-b is the AMIR roller compacted lane while the right-hand side labelled V-b is the vibratory train compacted lane.

Figure 5-10 Compaction Boxplot for AMIR and Vibratory Compacted Sections at Site 9.

Figure 5-11 Air Voids Boxplot for AMIR and Vibratory Compacted Sections at Site 9

Figure 5-12 Permeability Boxplot for AMIR and Vibratory Compacted Sections at Site 9

Figure 5-13 AMIR and the Vibratory Compacted Surfaces at Site 9

5.1.1 ANOVA of Common Trial Sites and Correlation Analysis

This section presents the analyses of variance (ANOVA) using SPSS 26 Statistical Software for the common trial sites where the AMIR and the vibratory train compactors were used to compact hot mix asphalt pavement sections. Also, the correlation matrix for the various variables and their significance are presented and discussed.

Table 5-4 is the ANOVA output of the measured variables extracted from Site 1 common to the two compactor types. The table output indicates that there are significant differences between the coefficient of permeability (K) and the indirect tensile strength (ITS) for the AMIR and the vibratory compacted sections at 5% level of significance. Comparing this ANOVA result with Figure 5-3 and Figure 5-4 indicates that even though for this specific site the field permeability coefficients of the section compacted by the vibratory train compactor are significantly lower than that of the AMIR compacted section, the AMIR section has higher indirect tensile strength (ITS) values compared to the vibratory train compacted section. Conversely, for compaction ($Comp$) and air voids (Va), there is marginally no significant difference between the AMIR and the vibratory compacted sections based on 5% level of significance. This is not unexpected because compaction was supposed to be controlled to keep the compaction level the same using a nuclear density gauge.

Table 5-4 ANOVA of Key Variables by Roller Type for Site 1

		<i>Sum of Squares</i>	<i>df</i>	<i>Mean Square</i>	<i>F</i>	<i>Sig.</i>
K	<i>Between Groups</i>	0.000140	1	140E-06	6.590	0.015
	<i>Within Groups</i>	0.000699	33	21.0E-06		
	<i>Total</i>	0.000839	34			
Comp	<i>Between Groups</i>	26.961	1	26.961	3.382	0.075
	<i>Within Groups</i>	263.039	33	7.971		
	<i>Total</i>	290.000	34			
Va	<i>Between Groups</i>	26.961	1	26.961	3.382	0.075
	<i>Within Groups</i>	263.039	33	7.971		
	<i>Total</i>	290.000	34			
ITS	<i>Between Groups</i>	207422.078	1	207422.078	11.763	0.002
	<i>Within Groups</i>	581895.802	33	17633.206		
	<i>Total</i>	789317.880	34			

On the other hand, if the 5% level of significance is not rigidly applied, one may argue that a p-value of 0.075 (7.5 %) for air voids and compaction indicates a significant difference between the two roller systems used in this site since the probability of rejecting a correct null hypothesis is only 7.5%. This difference indicates that the AMIR compacted section of this site has a higher compaction level (lower air voids) than the vibratory train compacted section of this site. This could be attributed to the lack of experience of the paving crew using the AMIR technology in the paving operations especially in the area of using the nuclear gauge in the monitoring compaction during paving operations.

For Site 2, Table 5-5 is the ANOVA results of the measured variables common to the two types of rollers. The *ITS* was found to be significantly different for the sections compacted by the AMIR and the vibratory train compactors. This indicates that the

strength of the section compacted by the AMIR roller has a higher strength value measured by the indirect tensile strength (*ITS*) compared to the section compacted by the vibratory train compaction method. However, for variables *K*, *Comp* and *Va*, there were no significant differences between the section compacted by the two compactors for Site 2 at a 5% level of significance.

Table 5-5 ANOVA of Key Variables by Roller Type for Site 2

		<i>Sum of Squares</i>	<i>df</i>	<i>Mean Square</i>	<i>F</i>	<i>Sig.</i>
<i>K</i>	<i>Between Groups</i>	7.99E-09	1	7.99E-09	0.208	0.654
	<i>Within Groups</i>	6.904E-07	18	3.350E-8		
	<i>Total</i>	6.983E-07	19			
<i>Comp</i>	<i>Between Groups</i>	0.076	1	0.0760	0.171	0.684
	<i>Within Groups</i>	7.963	18	0.442		
	<i>Total</i>	8.038	19			
<i>Va</i>	<i>Between Groups</i>	0.0756	1	0.0760	0.171	0.684
	<i>Within Groups</i>	7.963	18	0.442		
	<i>Total</i>	8.038	19			
<i>ITS</i>	<i>Between Groups</i>	1726.082	1	1726.082	34.724	0.000
	<i>Within Groups</i>	894.742	18	49.708		
	<i>Total</i>	2620.824	19			

Similarly, Table 5-6 is the ANOVA output for Site 7 showing that permeability coefficient (*K*) is significantly different for the sections compacted by the two compactors while the difference in *Comp*, *Va* and *ITS* for AMIR and the vibratory train compacted sections for this particular site is at the limit of or slightly higher than the 5% level of significance. This indicates that the sections compacted by the two different compactors are practically different with the AMIR compacted section yielding pavement with lower

permeability values compared to the vibratory train compacted section of Site 7. Furthermore, AMIR compacted section produces asphalt pavement with higher compaction level (lower air voids) and indirect tensile strength values. These differences although not intended can be attributed to the effectiveness of the non-destructive compaction monitoring device and probably the experience of the paving crews in keeping the sections at comparable air voids levels.

More so, Table 5-7 is the ANOVA output for Site 8 showing that permeability coefficient (K) is significantly different for the sections compacted by the two compactors while there is no significant difference in *Comp*, *Va* and *ITS* for AMIR and the vibratory train compacted sections. Again, this implies that AMIR compacted section of Site 8 has lower permeability values compared to the vibratory train compacted section of this site while there is no significant difference for the two compactors for the variables *Comp*, *Va* and *ITS*.

Table 5-6 ANOVA of Key Variables by Roller Type for Site 7

		<i>Sum of Squares</i>	<i>df</i>	<i>Mean Square</i>	<i>F</i>	<i>Sig.</i>
K	<i>Between Groups</i>	0.00108	1	1.08E-03	8.871	0.015
	<i>Within Groups</i>	0.00110	9	1.22E-04		
	<i>Total</i>	0.00217	10			
Comp	<i>Between Groups</i>	13.340	1	13.340	5.097	0.050
	<i>Within Groups</i>	23.557	9	2.617		
	<i>Total</i>	36.897	10			
Va	<i>Between Groups</i>	13.340	1	13.340	5.097	0.050
	<i>Within Groups</i>	23.557	9	2.617		
	<i>Total</i>	36.897	10			
ITS	<i>Between Groups</i>	155516.112	1	155516.112	4.686	0.059
	<i>Within Groups</i>	298710.451	9	33190.050		
	<i>Total</i>	454226.563	10			

Table 5-8 is the ANOVA output for Site 9 showing that permeability coefficient (*K*) and the number of passes (*Pass*) are significantly different for the sections compacted by the two compactors while there is no significant difference in *Comp*, *Va*, and the layer thickness (*Thick*) for AMIR and the vibratory train compacted sections. This implies that despite the AMIR compactor having a smaller number of passes, the section it compacted had lower permeability values compared to the sections compacted by the vibratory train compactor. Table 5-9 is the Pearson correlation matrix for the various variables computed with SAS 9.4 Statistical Software to evaluate the bivariate relationship or association between the various variables and their significances based on the null hypothesis that the correlation coefficient is equal to zero (hypothesized value) against an alternative hypothesis that the correlation coefficient is not equal to the hypothesized value. In the

table, there are three rows of values for each variable. The first row is the correlation coefficient, the second is the significance value (p-value) while the third is the number of data points used in the calculation of the correlation coefficient for that variable. The strength of the relationship between two variables or the classification of the correlation coefficient is weak, moderate, and strong as may be used in this work is based on Ratner (2009).

Table 5-7 ANOVA of Key Variables by Roller Type for Site 8

		<i>Sum of Squares</i>	<i>df</i>	<i>Mean Square</i>	<i>F</i>	<i>Sig.</i>
K	<i>Between Groups</i>	0.000104	1	1.04E-04	6.446	0.021
	<i>Within Groups</i>	0.000290	18	1.60E-05		
	<i>Total</i>	0.000393	19			
Comp	<i>Between Groups</i>	5.523	1	5.523	2.087	0.166
	<i>Within Groups</i>	47.637	18	2.646		
	<i>Total</i>	53.160	19			
Va	<i>Between Groups</i>	5.523	1	5.523	2.087	0.166
	<i>Within Groups</i>	47.637	18	2.646		
	<i>Total</i>	53.160	19			
ITS	<i>Between Groups</i>	1.022	1	1.022	0.003	0.957
	<i>Within Groups</i>	6059.388	18	336.633		
	<i>Total</i>	6060.409	19			

Table 5-8 ANOVA of Key Variables by Roller Type for Site 9

		<i>Sum of Squares</i>	<i>df</i>	<i>Mean Square</i>	<i>F</i>	<i>Sig.</i>
K	<i>Between Groups</i>	0.000059	1	5.90E-05	6.618	0.016
	<i>Within Groups</i>	0.000252	28	9.0E-06		
	<i>Total</i>	0.000311	29			
Comp	<i>Between Groups</i>	5.998	1	5.998	1.855	0.184
	<i>Within Groups</i>	90.541	28	3.234		
	<i>Total</i>	96.539	29			
Va	<i>Between Groups</i>	5.998	1	5.998	1.855	0.184
	<i>Within Groups</i>	90.541	28	3.234		
	<i>Total</i>	96.539	29			
Pass	<i>Between Groups</i>	1178.133	1	1178.133	70.286	0.000
	<i>Within Groups</i>	469.333	28	16.762		
	<i>Total</i>	1647.467	29			
Thick	<i>Between Groups</i>	56.033	1	56.033	0.346	0.561
	<i>Within Groups</i>	4534.667	28	161.952		
	<i>Total</i>	4590.700	29			

Table 5-9 Correlation Matrix of Variables

		Pearson Correlation Coefficients Prob > r under H0: Rho(ρ) = 0 Number of Observations							
		K	Comp	Va	ITS	Pavt	Thick	Passes	Rol
K	<i>r</i>	1.00000	-0.35891	0.35891	0.39919	0.65145	-0.08769	0.00422	-0.03669
	<i>p-value</i>		<.0001	<.0001	<.0001	<.0001	0.2672	0.9575	0.6430
	<i>N</i>	162	162	162	132	162	162	162	162
Comp	<i>r</i>	-0.35891	1.00000	-1.00000	0.07776	-0.34071	-0.04443	-0.02611	0.11818
	<i>p-value</i>	<.0001		<.0001	0.3755	<.0001	0.5745	0.7416	0.1342
	<i>N</i>	162	162	162	132	162	162	162	162
Va	<i>r</i>	0.35891	-1.00000	1.00000	-0.07776	0.34071	0.04443	0.02611	-0.11818
	<i>p-value</i>	<.0001	<.0001		0.3755	<.0001	0.5745	0.7416	0.1342
	<i>N</i>	162	162	162	132	162	162	162	162
ITS	<i>r</i>	0.39919	0.07776	-0.07776	1.00000	0.48533	.	-0.02769	0.02769
	<i>p-value</i>	<.0001	0.3755	0.3755		<.0001	.	0.7526	0.7526
	<i>N</i>	132	132	132	132	132	132	132	132
Pavt	<i>r</i>	0.65145	-0.34071	0.34071	0.48533	1.00000	-0.10523	0.02519	-0.00482
	<i>p-value</i>	<.0001	<.0001	<.0001	<.0001		0.1826	0.7503	0.9515
	<i>N</i>	162	162	162	132	162	162	162	162
Thick	<i>r</i>	-0.08769	-0.04443	0.04443	.	-0.10523	1.00000	-0.12370	0.09705
	<i>p-value</i>	0.2672	0.5745	0.5745	.	0.1826		0.1168	0.2192
	<i>N</i>	162	162	162	132	162	162	162	162
Pass	<i>r</i>	0.00422	-0.02611	0.02611	-0.02769	0.02519	-0.12370	1.00000	-0.96050
	<i>p-value</i>	0.9575	0.7416	0.7416	0.7526	0.7503	0.1168		<.0001
	<i>N</i>	162	162	162	132	162	162	162	162
Rol	<i>r</i>	-0.03669	0.11818	-0.11818	0.02769	-0.00482	0.09705	-0.96050	1.00000
	<i>p-value</i>	0.6430	0.1342	0.1342	0.7526	0.9515	0.2192	<.0001	
	<i>N</i>	162	162	162	132	162	162	162	162

Ratner (2009) suggested that correlation coefficient between 0 and (+/-) 0.3 is weak, between (+/-) 0.3 and (+/-) 0.7 moderate and between (+/-) 0.7 and (+/-) 1 strong. When the correlation coefficient has a negative value, it means that an increase in one variable causes a corresponding decrease in the second variable vice versa. From Table 5-9, the permeability coefficient (K) has a significant moderate negative correlation coefficient with compaction ($Comp$), indicating that an increase in compaction level reduces the ability of the compacted asphalt pavement to admit water i.e., a decrease in permeability. This is not surprising given that increasing compaction increases the densification and packing together of the particles that make up the asphalt concrete thereby closing the paths through which water could pass. Further examination of the correlation matrix indicates the permeability coefficient (K) has a significant positive moderate correlation with the air voids (Va), significant positive moderate correlation with indirect tensile strength (ITS) and significant positive moderate correlation with the base type ($Pavt$). The positive correlation of field permeability with the indirect tensile strength was unexpected and against the theory. This could be an indication that field permeability cannot be explicitly explained by compaction level alone. Alternatively, it could be due to the impacts of the steel drum roller-induced cracks that altered the expected trend of the ITS with permeability. The positive correlation of air voids (Va) with permeability coefficient (K) stems from the known fact that the increase in air voids increases the propensity of the asphalt concrete to be permeable.

Furthermore, the air voids (Va) has a moderate positive significant correlation with the base type ($Pavt$). This implies that pavements compacted on a more rigid base would

have higher air voids compared to those compacted on a more flexible base. Similarly, *ITS* has a significant moderate positive correlation with the *P_{avt}*. This again signifies that pavements compacted on a more rigid base have a higher strength indicator as measured with *ITS* than those compacted on a more flexible base. This is despite the surfaces compacted on a more rigid base having lower compaction values compared to those compacted on a granular base. This suggests that higher compaction values do not necessarily correlate with higher strength values represented by the *ITS*.

5.1.2 Ordinary Least Square Modelling of Field Permeability and Influential Factors

This section presents the ordinary least square regression analyses based on the 162 samples extracted from the nine (9) projects across Eastern Ontario MTO Regional Office compacted using the AMIR roller and the conventional vibratory steel drum compaction trains. This section aims to study the relationship between the major variables and permeability. To do this, ordinary least square (OLS) regression analysis using SAS 9.4 Statistical Software is used in the OLS modelling approach. The major aim is not to fully predict permeability but rather to highlight the major field and construction variables that affect permeability and to understand their interrelationships.

First, all the variables as mentioned in Section 3.4.1 were included in the trial model and examined for their significant effects or relationships with field permeability as well as multicollinearity among the independent variables using tolerance and variance inflation statistics. As mentioned earlier, compaction (*Comp*) measures the degree of packing together of the various particles that make up the asphalt concrete under load or pressure to reduce the inter-particle spaces. It is the ratio of the bulk density (*G_{mb}*) to the maximum

theoretical density (G_{mm}) as explained in Section 3.3.2 expressed in percent (%). This way, the inter-particle spaces that would have been occupied by water are reduced thereby reducing permeability. Similarly, the air voids (V_a) measure the inter-particle spaces that exist in the mix and are equally expressed in percent (%) as explained in Section 3.3.2. The air voids and compaction are inversely related such that the higher the compaction, the lower the air voids vice versa. Thus, an increase in the air voids is expected to be associated with an increase in the permeability of the mix controlling for other factors.

Also, for the indirect tensile strength (ITS), it is expected that an increase in compaction would result in increased ITS and hence a reduced permeability of the compacted asphalt mix. The base type (P_{avt}) is a dichotomised variable with zero (0) representing a compacted granular base and one (1) representing a concrete base. Not a lot has been studied about the impact of the base type on the permeability of asphalt concrete. However, one would expect that controlling for other factors, density should be higher for asphalt concrete compacted on the concrete base thereby reducing permeability compared to asphalt concrete compacted on the granular base. The compactor type variable (R_{ol}) is also a dichotomised (dummy) variable with zero (0) for the vibratory train compaction methods which is the reference group and one (1) for the AMIR compactor which is the comparison group. It is expected that at comparable compaction level ($Comp$) given the theories of operations of the two compactors, that the AMIR roller could produce pavement systems devoid of roller checking or surface cracks thereby limiting the amount of water that would reach the core of the asphalt road pavements.

Furthermore, permeability is expected to decrease with an increase in the mix design variables such as asphalt content (A_c) and vice versa. Higher asphalt content is

expected to help fill and clog the void and pathways where water is expected to flow through. Similarly, permeability is also expected to decrease with increasing compaction temperature (*ComTem*) because, the higher the temperature at compaction, the lower the viscosity of the binder and easier it is to achieve higher compaction thereby reducing permeability. The gradation variable (*Dust*) reflects the percentage by weight of finest filler materials that would help clog the pores in the mix thereby reducing the permeability of the mix. The fine aggregates variables based on percentage passing designated sieve sizes such as sieve No. 4, sieve No. 8 (variables referred to as *S4* and *S8*, respectively) and the proportion of reclaimed asphalt content (*RAP*) are all expected to help reduce the permeability of the compacted asphalt mix. Increasing performance grading (PG) upper temperature (*PGh*) is expected to be associated with increased permeability as the asphalt cement may be stiffer and more viscous therefore difficult to compact while and the opposite is expected with lower temperature (*PGl*) temperatures. The various *project locations* (*Site 1 to Site 9*) are expected to capture the site-specific effects on field permeability.

Table 5-10 shows the SAS output for the trial model with all the independent variables with their respective variance inflation statistic values. The variance inflation factor (VIF) of a given independent variable under investigation is the ratio of the overall model variance to the proportion of unexplained variance of that variable when regressed on other explanatory (independent) variables. Tolerance is the inverse of the VIF. There is no strict rule on the baseline of acceptable VIF values, however, VIF values ranging between 5 and 10 are recommended by Tay (2017).

Hence, a close look at the correlation matrix of Table 5-9 and comparing that with Table 5-10 shows that percentage of air voids (Va) was perfectly correlated to relative compaction ($Comp$). Also, a close look at the DF (column) of Table 5-10 has Bs indicating biased estimates and the various large VIF values. Since Gmm and Gmb are used in computing $Comp$, and Va linearly related to $Comp$; Va , Gmm and Gmb were removed from the list as independent variables as standalone variables. However, Va is still retained in interaction variables because of the focus of the literature and theory on the relationship of air voids and permeability. More so, the mix variables were also removed given that none of the variables significantly affects field permeability in the trial model. This could be that there was not enough variation between field permeability and the various mix types since they were essentially the same designation for all the sites even though their sources and gradations are slightly different. Table 5-11 shows that the VIF of the variables are all less than 10 although the estimates of the degrees of freedom for some independent variables are still biased.

Various interaction terms were evaluated to examine their contributions in the various variables' interrelationships. For instance, square and cubic forms of the air voids (Va) were evaluated to determine the existence of a power relationship of permeability and air voids, as widely reported in the literature as well as the product i.e. joint effects of air voids with the roller type Rol and base type $Pavt$. This was done to investigate and determine the joint effect of the roller at each level of the air voids on permeability. As a result, the interaction term $VaRol$ is expected to capture the joint effect of air voids, its different categories, and the roller types, on the resulting permeability of field compacted asphalt pavement surfaces. Also, the interaction term $Va^2RolPavt$ would capture the joint

Table 5-10 Multicollinearity Diagnosis of the Trial OLS Model

<i>Variable</i>	<i>DF</i>	<i>Parameter Estimate</i>	<i>Standard Error</i>	<i>Pr > t </i>	<i>Standardized Estimate</i>	<i>Variance Inflation</i>
<i>Intercept</i>	<i>B</i>	0.01402	0.32812	0.9660	0	0
<i>Comp</i>	<i>B</i>	-0.00022951	0.00304	0.9400	-0.07276	247.22966
<i>Va</i>	<i>0</i>	0	.	.	.	.
<i>Gmm</i>	<i>B</i>	-0.00821	0.12135	0.9461	-0.05332	165.00139
<i>Gmb</i>	<i>B</i>	-0.00377	0.11933	0.9748	-0.02789	206.71991
<i>ITS</i>	<i>B</i>	0.00000776	0.00000544	0.1565	0.19030	4.73614
<i>Pavt</i>	<i>B</i>	0.01419	0.00912	0.1225	0.59450	38.83988
<i>Rol</i>	<i>B</i>	-0.00267	0.00130	0.0429	-0.17171	1.87107
<i>Thick</i>	<i>0</i>	0	.	.	.	.
<i>Pass</i>	<i>0</i>	0	.	.	.	.
<i>ComTem</i>	<i>B</i>	-0.00038376	0.00091627	0.6761	-0.34949	185.13162
<i>PGH</i>	<i>B</i>	-0.00049425	0.00056686	0.3850	-0.18119	11.48174
<i>PGL</i>	<i>B</i>	-0.00188	0.00294	0.5237	-1.08593	766.71855
<i>AC</i>	<i>B</i>	0.02257	0.03762	0.5497	0.98142	711.62536
<i>Rap</i>	<i>B</i>	0.04982	0.06883	0.4706	2.25357	2577.23600
<i>Dust</i>	<i>B</i>	-0.06525	0.06734	0.3346	-0.74073	155.39802
<i>PAN</i>	<i>0</i>	0	.	.	.	.
<i>VMA</i>	<i>0</i>	0	.	.	.	.
<i>S4</i>	<i>0</i>	0	.	.	.	.
<i>S8</i>	<i>0</i>	0	.	.	.	.
<i>VFA</i>	<i>0</i>	0	.	.	.	.
<i>Site 1</i>	<i>0</i>	0	.	.	.	.
<i>Site 2</i>	<i>0</i>	0	.	.	.	.
<i>Site 3</i>	<i>0</i>	0	.	.	.	.
<i>Site 4</i>	<i>0</i>	0	.	.	.	.
<i>Site 5</i>	<i>0</i>	0	.	.	.	.
<i>Site 6</i>	<i>0</i>	0	.	.	.	.
<i>Site 7</i>	<i>0</i>	0	.	.	.	.
<i>Site 8</i>	<i>0</i>	0	.	.	.	.

<i>Site 9</i>	0	0	.	.	.	.
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Table 5-11 Multicollinearity Resolution of the Trial OLS Model

<i>Variable</i>	<i>DF</i>	<i>Parameter Estimate</i>	<i>Standard Error</i>	<i>Pr > t </i>	<i>Standardized Estimate</i>	<i>Variance Inflation</i>
<i>Intercept</i>	<i>B</i>	0.00595	0.00169	0.0006	0	0
<i>Comp</i>	<i>1</i>	-0.00032651	0.00029260	0.2667	-0.10351	2.32497
<i>ITS</i>	<i>1</i>	0.00000774	0.00000538	0.1531	0.18971	4.70484
<i>Pavt</i>	<i>B</i>	0.01326	0.00358	0.0003	0.55551	6.08446
<i>Rol</i>	<i>B</i>	-0.00264	0.00129	0.0425	-0.16949	1.84714
<i>Thick</i>	<i>0</i>	0	.	.	.	.
<i>Pass</i>	<i>0</i>	0	.	.	.	.
<i>Site 1</i>	<i>B</i>	0.00014924	0.00173	0.9314	0.00870	2.74499
<i>Site 2</i>	<i>B</i>	-0.00252	0.00184	0.1742	-0.11914	2.05275
<i>Site 3</i>	<i>B</i>	-0.00571	0.00259	0.0292	-0.23918	3.17515
<i>Site 4</i>	<i>B</i>	-0.00375	0.00237	0.1165	-0.14220	2.18591
<i>Site 5</i>	<i>B</i>	-0.00482	0.00241	0.0479	-0.20189	2.75880
<i>Site 6</i>	<i>B</i>	-0.00954	0.00364	0.0099	-0.21600	1.83766
<i>Site 7</i>	<i>0</i>	0	.	.	.	.
<i>Site 8</i>	<i>0</i>	0	.	.	.	.
<i>Site 9</i>	<i>0</i>	0	.	.	.	.

effect of the power-law relationship of the air voids, the compactor types, and the underlying base types. Furthermore, another interaction term *PavtRol* captures the effect of compacting on a more rigid base like the bridge decks with conventional compaction technologies and AMIR. Finally, individual project locations (Site 1 to Site 9) were included in the model to evaluate their various effects on field permeability.

Several model forms and transformations of some variables were tried and evaluated. An extensive search for the important and significant independent variables, and interactions among the predictor variables while paying attention to the problem of multicollinearity and project locations, indicated that relative compaction (*Comp*), pavement type (*Pavt*), the number of passes of the roller, the interaction terms *VaRol*, *PavtRol*, $Va^2RolPavt$ and project locations; *Site 2* and *Site 7* are significant at a 5% level of significance. Table 5-12 shows the SAS output ANOVA of the OLS model and the significance of the model in predicting field permeability based on the data and the variables used while Table 5-13 shows the goodness of fit of the OLS model. Based on the output shown in Table 5-13, the model explained 66.7% of the observed variation in field permeability leaving 33.3% as the unexplained variation which could be attributed to the controlled factors in the various field compaction trials. Table 5-14 shows the parameter estimates of the significant independent variables and the applicable interaction terms. Equation (5.0) shows the linear regression model of the interrelationships among the major variables retained with respect to field permeability as the dependent variable.

Table 5-12 SAS 9.4 OLS Model ANOVA

<i>Analysis of Variance</i>					
<i>Source</i>	<i>DF</i>	<i>Sum of Squares</i>	<i>Mean Square</i>	<i>F Value</i>	<i>Pr>F</i>
<i>Model</i>	8	0.00526	0.00065711	38.29	<.0001
<i>Error</i>	153	0.00263	0.00001716		
<i>Corrected Total</i>	161	0.00788			

Table 5-13 Model Goodness of Fit

<i>Root MSE</i>	0.00414	<i>R-Square</i>	0.6669
<i>Dependent Mean</i>	0.00428	<i>Adj R-Sq</i>	0.6495
<i>Coeff Var</i>	96.8913		

Table 5-14 Parameter Estimates for the Independent Variables and Interactions

<i>Variable</i>	<i>Parameter Estimate</i>	<i>Standard Error</i>	<i>p-value</i>	<i>Standard Estimate</i>
<i>Intercept</i>	0.0070	0.0013	<0.0001	0
<i>Comp</i>	-0.00070	0.00022	0.0022	-0.24
<i>Pavt</i>	0.0063	0.0022	0.0041	0.263
<i>Pass</i>	-0.000202	0.000067	0.0028	-0.21
<i>VaRol</i>	-0.00070	0.00028	0.0130	-0.23
<i>PavtRol</i>	-0.011	0.0040	0.0053	-0.302
<i>Va²RolPavt</i>	-0.00027	0.00011	0.0190	-0.21
<i>Site 2</i>	-0.0026	0.0010	0.0130	-0.12
<i>Site 7</i>	0.02040	0.0028	<0.0001	0.74

$$\begin{aligned}
K &= 0.0070 - 0.00070Comp + 0.0063Pavt \\
&\quad - 0.000202Passes - 0.00070VaRol \\
&\quad - 0.011PavtRol - 0.00027Va^2RolPavt \\
&\quad - 0.0026Site2 + 0.02040Site7
\end{aligned}
\tag{5.0}$$

An inverse relationship between the coefficient of permeability K and the relative compaction $Comp$, number of roller passes $Pass$ and their interaction terms $VaRol$, $PavtRol$ and $Va^2RolPavt$ was observed. Recall that the respective sites were individually included as independent dummy variables in the model with only *Site 2* and *Site 7* being the only site locations that were significant among the nine (9) locations used. The coefficient of the $Comp$ variable is -0.00070 which is the slope or the amount by which permeability would decrease per unit increase in compaction controlling for other variables in the model. This is in agreement with the theory that an increase in compaction brings together the various particles that make up the asphalt concrete, therefore reducing the amount of voids in the mix which in turn reduces permeability. This is especially the case given that compaction ($Comp$) was not uniformly controlled i.e. kept at the same comparable level of compaction across the nine sites. This could either be a result of the nuclear gauge reliability, accuracy or the crew's experience.

Meanwhile, for the dummy variable $Pavt$; it was observed that the mean permeability would be greater for a new asphalt layer placed upon a milled or concrete base by 0.0063 compared to a more flexible compacted granular base controlling for the effects of other variables in the model. This result is particularly important in evaluating pavements compacted over bridge decks where operating the conventional steel drum

compactors in vibration modes is not permitted. The possible explanation for this observation is the lack of vibration of the compacted mix by the vibratory steel drum compactor as stipulated by the governing specifications yielding lower compaction values for asphalt concrete compacted on bridge deck concrete as may be seen in Figure 5-5 and Figure 5-6. Also, this observation could be possibly attributed to the inability of the rigid concrete base to absorb and deform under the compaction energy of the roller to allow proper orientation of the aggregates in the hot asphalt concrete to yield adequate compaction. Also, the negative value of the *VaRol* interaction term coefficient indicates that the mean permeability coefficient of the pavement sections decreases with the use of AMIR roller by 0.00070 per unit air voids compared to the conventional steel-drum compactor (vibratory + pneumatic train compaction) controlling for other variables in the model. This suggests that even though the pavement system compacted by the two different methods of compaction may be at the same air voids level, the section compacted by the vibratory compaction train would be more permeable than the AMIR compacted section. This is mainly because of the cracks induced by the steel drum on the asphalt concrete surfaces which further connects the air voids in the mix leading to higher permeability of the vibratory roller compacted surfaces. The number of roller pass expectedly was observed to reduce the permeability of the compacted sections by 0.000202 for each additional pass which agrees with the theory.

Furthermore, the interaction term *PavtRol* indicates that using the AMIR compactor to compact asphalt concrete on more rigid bases like concrete base against the compacted granular base would reduce the mean permeability coefficient of the compacted mix by 0.011 compared to conventional compactor controlling for other variables in the

model. This is especially so given that the conventional steel drum compactor did not operate in the vibratory mode when used on the bridge deck concrete be. Similarly, the interaction term $Va^2RolPavt$ suggests that at a given air voids level, using the AMIR compactor on a rigid base against the compacted granular base would reduce mean pavement permeability per unit increase in air voids by 0.00027 compared to the vibratory steel drum compaction controlling for other variables in the model. This equally validates the notion of the power-law relationship of permeability with the air voids.

In the case of the various sites included as dummy variables in the model, while *Site 2* indicates a reduction in permeability, *Site 7* indicates an increase in permeability in these sites compared to all other sites. This could be attributed to the differences in paving factors such as crew members, sources and characteristics of construction materials, weather etc. Specifically, Figure 5-1 and Figure 5-2 reveals that the vibratory steel drum compactor has a marginally low compaction level and higher air voids than the AMIR compactor. Similarly, for *Site 2*, both compactors compacted sections that have marginally higher compaction levels, lower air voids and tighter spread compared to other sites which explained it has the least permeability. Also, as stated earlier this could be a result of the nuclear gauge reliability, accuracy or the crew's experience. Further examination of the standard parameter estimates given in Table 5-14 indicates that the most important variables or interaction terms affecting permeability in decreasing order are *Site 7*, *PavtRol*, *Pavt*, *Comp*, *VaRol*, $Va^2RolPavt$, *Pass*, and *Site 2*.

5.1.3 Mixed Modelling of the Effect of Project Location on Field Permeability

The ordinary least square regression is based on underlying assumptions. Major assumptions of OLS include the assumption of linearity, mean independence and normal

distribution of the error term, uncorrelated error, homogeneous variance, and absence of collinear independent variables. The linear mixed model however provides the flexibility of regression modelling of not only the means of the data but also the variances and covariances in the data. The variations observed in the field permeability values measured were not unexpected to vary with the various project locations. Thus, measurements taken or nested within a project location are expected to be correlated thus violating some of the underlying assumptions of OLS which could severely affect the outcome and thus the interpretation of the OLS results. This is because the unique construction and other geographical location factors may be of great significant importance in explaining the variations in field permeability given that the two sites i.e. *Site 2* and *Site 7* were found to be significant in explaining the observed variations in field permeability using the OLS modelling approach detailed in Section 5.1.2 above. The inclusions of the various sites (location) in the mixed modelling technique were to evaluate and quantify the random effect of various project sites (location) on the observed variations in field permeability.

The main objective of mixed modelling is to quantify the proportion of random variation and estimate the significance of the group effect factor, which is in this case, the project location on the field permeability. Unlike the OLS however, the mixed modelling approach is not straightforward and there are key decisions that have to be made *ab initio* which in turn could potentially affect the outcome of the analysis. For instance, the estimation method, the type of degrees of freedom and the structure of the covariance matrix. The mixed modelling provides a better mechanism for handling missing values and a well-suited degree of freedom types for unbalanced designs (Bell et al., 2013; Wolfinger and Chang 1995). The mixed model building approach starts by first deciding the degree

of freedom type and the covariance structure. The Kenward-Roger and Satterthwaite degrees of freedom methods are well suited for most mixed models as they are both intended to be used in models with unbalanced designs and both could also handle complex covariance structures (Bell et al., 2013). For the covariance structures, it is recommended that the variance components be tried first as that is the simplest covariance structure among the various types. Finally, the estimation method has to be decided. The restricted maximum likelihood estimation method has been shown in many cases to have less bias than the maximum likelihood estimation method in the variance and covariance estimation especially for small samples (Wu et al., 2001). Thus, the restricted maximum likelihood estimation method which is the default estimation method in SAS is used in the mixed modelling approach of the field permeability.

Table 5-15 shows the SAS 9.4 mixed model approach and information that were used in evaluating the general significance of the various locations of the projects used in studying the effects of field compaction on permeability. The model building method starts by examining the unconditional model with no predictors to assess the proportion of variation in field permeability accounted by the project location (Site No) and to assess the significance of the intraclass correlation coefficient (ICC) in order to justify whether mixed modelling is warranted or not.

Table 5-15 Multilevel Model Information

Model Information	
<i>Dependent Variable</i>	<i>K (coefficient of permeability)</i>
<i>Covariance Structure</i>	<i>Variance Components</i>
<i>Subject Effect</i>	<i>Location (Site No)</i>
<i>Estimation Method</i>	<i>REML</i>
<i>Residual Variance Method</i>	<i>Profile</i>
<i>Fixed Effects SE Method</i>	<i>Kenward-Roger</i>
<i>Degrees of Freedom Method</i>	<i>Kenward-Roger</i>

Equation (5.1) is the unconditional model ICC expression and Table 5-16 is the covariance parameter estimates for the unconditional model where $\sigma_{Location}^2$ is the variance estimate for the project location and $\sigma_{Residual}^2$ is the error variance estimate. Evaluation of Equation (5.1) shows that the ICC is 0.62 which implies that the proportion of variation in field permeability accounted by the location of the project sites is 62% and it is significant. Table 5-17 is the unconditional model fit statistics. Hence, a justification to further explore mixed modelling for the field permeability is valid.

$$\text{Equation } ICC = \frac{\sigma_{Location}^2}{\sigma_{Location}^2 + \sigma_{Residual}^2} = \frac{0.000042}{0.000042 + 0.000025} = 0.62 \quad (5.1)$$

Table 5-16 Covariance Parameter Estimates of the Unconditional Model

<i>Cov Parm</i>	<i>Subject</i>	<i>Estimate</i>	<i>Standard Error</i>	<i>Z Value</i>	<i>Pr > Z</i>
<i>Intercept</i>	<i>Location</i>	0.000042	0.000022	1.89	0.0292
<i>Residual</i>		0.000025	0	8.74	<.0001

Table 5-17 Unconditional Model Fit Statistics

<i>-2 Res Log Likelihood</i>	<i>-1215.9</i>
<i>AIC (Smaller is Better)</i>	<i>-1211.9</i>
<i>AICC (Smaller is Better)</i>	<i>-1211.8</i>
<i>BIC (Smaller is Better)</i>	<i>-1211.5</i>

Given the significance of the unconditional model, predictors are now added to the unconditional model in the model building process to evaluate field permeability. Several mixed models based on random intercept first, thereafter, random intercept and slope approaches were tried. The random intercept mixed model with fixed effects as the independent variables of the OLS model of Equation (5.0) and interaction terms without *Site 2* and *Site 7* was evaluated. Table 5-18 shows the estimates of the “*Location*” of the various sites to be insignificant as produced by SAS 9.4 Statistical Software.

Table 5-18 Covariance Parameter Estimates for Location

<i>Cov Parm</i>	<i>Subject</i>	<i>Estimate</i>	<i>Standard Error</i>	<i>Z Value</i>	<i>Pr > Z</i>
<i>Intercept</i>	<i>Location</i>	0.000025	0.000016	1.61	0.0542
<i>Residual</i>		0.000018	2.07E-06	8.59	<.0001

Table 5-19 shows that the various fixed independent variables and the applicable interaction terms as used in the OLS model to be significant as found earlier in Table 5-14 without the $Va^2RolPavt$, *Site 2* and *Site 7* terms. Fixed effects variables such as *Comp*, *Pavt*, *Passes*, *VaRol* and *PavtRol* as included in the OLS model were all found to be significant at a 5% level of significance. Table 5-20 is the fit statistics for the random intercept model with fixed effect variables shown in Table 5-19.

Table 5-19 Fixed Effects and Parameters

<i>Effect</i>	<i>Estimate</i>	<i>Standard Error</i>	<i>DF</i>	<i>t Value</i>	<i>Pr > t </i>
<i>Intercept</i>	0.08098	0.02194	156	3.69	0.0003
<i>Comp</i>	-0.00058	0.000224	154	-2.6	0.0102
<i>Pavt</i> (granular base = 0; concrete base = 1)	-0.0173	0.004348	7.03	-3.98	0.0053
<i>Pass</i>	-0.00034	0.000127	152	-2.64	0.0091
<i>VaRol</i>	-0.00063	0.000222	150	-2.82	0.0054
<i>PavtRol</i>	-0.01612	0.002815	155	-5.72	<.0001

Table 5-20 Fit Statistics for Random Intercept with Fixed Effect Predictors

<i>-2 Res Log Likelihood</i>	-1211.5
<i>AIC (Smaller is Better)</i>	-1207.5
<i>AICC (Smaller is Better)</i>	-1207.4
<i>BIC (Smaller is Better)</i>	-1207.1

Comparing the unconditional model fit statistics of Table 5-17 and with the fit statistics of the random intercept model with fixed effect variables of Table 5-20 indicates that the addition of the fixed effect variables did not improve the fitness of the model although it does provide significant interrelationships between the various fixed effect variables which agrees mostly with the OLS Equation (5.0) which is one of the objectives of this work. Further attempts to evaluate the random intercept and slope mixed modelling approach did not yield any significant or meaningful results. For instance, the fixed effect variables in Table 5-19 were included in the random intercept and slope modelling attempts. The results showed that the convergence criteria were met even though the final Hessian was not positive definite. Several other random intercept with and without slope model forms were tried and when the convergence criteria were met or not even with smaller values of the fit statistics showed that there were no significant random effect

variables for the mixed model. Results of these analyses are presented in Table C. 3 through Table C. 13.

5.2 Compaction and Permeability of Three Different Field Compactors

This section presents results and analyses of Case 2 field compaction and permeability studies shown in Figure 3-1. As mentioned in Section 3.2.3, *Site 10* test section was compacted using AMIR roller, vibratory compaction train, and HAMM oscillatory compaction train to compare the effects of two main compaction technologies against AMIR on field compaction and permeability and to also check the difference between vibratory and oscillatory steel drum compaction technologies. Based on the test strip plan of Figure 3-4 constructed at *Site 10*, The AMIR and oscillatory compaction train compacted sections had a binder and wearing course layers while AMIR and vibratory train compaction had only a wearing course layer. Cores were taken and permeability measurements using the NCAT were made on the compacted sections. Table 5-21 shows the compaction and permeability information of the binder course section where AMIR and oscillatory drum rollers were used side-by-side. Again, as mentioned earlier, density was controlled using the nuclear gauge for *Site 10* to keep the compacted test section by different compactors at the same level of compaction.

Table 5-21 Binder Course Compaction and Permeability for AMIR and Oscillatory Steel Drum Compactors

<i>Compactor</i>		<i>Nos of Samples (Comp.)</i>	<i>Va (%)</i>	<i>Compaction (%)</i>	<i>Nos of Samples (Perm.)</i>	<i>Field Permeability (cm/sec)</i>
<i>AMIR</i>	<i>Mean</i>	4	9.72	90.28	5	1.13E-03
	<i>Std Dev</i>		2.04	2.04		2.62E-04
<i>Oscillatory</i>	<i>Mean</i>	6	8.58	91.42	14	2.38E-03
	<i>Std Dev</i>		2.41	2.41		1.28E-03

Figure 5-14 is the boxplot of percent compaction of the AMIR and the oscillatory roller compacted section of the binder course. The plots show that the oscillatory roller compaction is marginally higher than the AMIR compacted section. Figure 5-15 presents the NCAT permeameter permeability coefficients by tier for the binder course, and it could be seen that the AMIR compacted section has consistently lower permeability values than the oscillatory steel drum compacted section of the binder course as well as less variability in all the three tiers. AMIR made eight passes while the oscillatory compactor made fifteen passes to achieve compaction.

Figure 5-14 Binder Course Compaction of the Sections Compacted by Three Different Compaction Technologies

Figure 5-15 NCAT Tier Permeability of the AMIR and Oscillatory Drum Binder Course

Figure 5-16 shows the compacted surfaces of the AMIR and the HAMM Oscillating drum compactors close to the longitudinal joint. The left-hand side of the picture is the AMIR compacted side of the joint and the dark-chalky right-hand side is the oscillatory drum roller-compacted surface. This goes to highlight the effects of oscillatory steel drum compaction on the compacted asphalt pavement surface and by extension the resulting properties of asphalt concrete. This roller-induced cracks and bridging of the aggregates as seen in Figure 5-16 are also not different from that between the AMIR and the vibratory steel drum roller compacted surfaces shown earlier in Figure 5-13. This shows that regardless of whether the steel drum vibrates or oscillates, the resultant effects of the drums on the compacted surface of asphalt concrete are the same.

Figure 5-16 AMIR and HAMM Oscillatory Compacted Surfaces

Table 5-22 shows the compaction and field permeability information of the three compactor types for the wearing course for the AMIR single roller, oscillatory and the vibratory compaction trains. Figure 5-17 shows the boxplot of percent compaction for each compactor type for the wearing course with the AMIR compactor showing marginally higher percent compaction than the oscillatory and the vibratory compactors. Figure 5-18 is the boxplot of NCAT tier permeability for the three compactors. While the AMIR and the oscillatory section do not have the tier 4 permeability compared to the vibratory steel drum; AMIR had the least permeability of all the three compactors consistently in the first three tiers.

Table 5-22 Wearing Course Compaction and Permeability for AMIR and Oscillatory Steel Drum Compactors

<i>Roller Types</i>	<i>Descriptive Statistics</i>	<i>Nos of Samples (Comp.)</i>	<i>Comp. (%)</i>	<i>Nos of Samples (Perm)</i>	<i>Field Permeability</i>
<i>Oscillatory</i>	<i>Mean</i>	<i>6</i>	<i>90.50</i>	<i>23</i>	<i>3.42E-03</i>
	<i>Std Dev</i>		<i>1.53</i>		<i>3.10E-03</i>
<i>AMIR</i>	<i>Mean</i>	<i>11</i>	<i>91.54</i>	<i>42</i>	<i>1.30E-03</i>
	<i>Std Dev</i>		<i>1.29</i>		<i>1.01E-03</i>
<i>Vibratory</i>	<i>Mean</i>	<i>6</i>	<i>90.44</i>	<i>22</i>	<i>3.47E-03</i>
	<i>Std Dev</i>		<i>2.14</i>		<i>2.98E-03</i>

Figure 5-17 Wearing Course Compaction of the Sections Compacted by Three Different Compaction Technologies

Figure 5-18 NCAT Tier Permeability of the AMIR and Oscillatory Drum Wearing Course

To further investigate and compare the effects of the compaction technologies available to the asphalt paving industry with respect to the objectives outlined in Section 1.3, and the research plan in Figure 3-1; analyses of variance (ANOVA) were employed to evaluate potential differences in the measured properties of the compacted surfaces at Site 10. Figure 5-19 is the compaction boxplot of all the cores for the Superpave gyratory compacted (SGC) and the various field compactors. Recall that the compaction level in the field was controlled for the three different field compactor and the SGC specimens were produced to similar volumetric characteristics with the field cores. Thus, from Figure 5-19, the dispersion of the data could be said to be fairly similar. For the percent compaction of the compactor types; a statistical test of the hypothesis that the field compaction (measured from the recovered cores) of the compacted sections by the different compactors are equal was conducted in SPSS statistical software. Analysis of variance (ANOVA) results

indicates that there was no significant difference between the densities (compaction) of the sections compacted by the three different types of field compaction methods at a 5% level of significance. Furthermore, there is no significant difference between the SGC compacted samples, and the cores compacted by the three different field compactors. Table 5-23 is the ANOVA table for the SGC and the different field compacted cores. Details of the data are provided in 6.2Appendix E

Figure 5-19 Boxplot Plot of Compaction of All Field and Laboratory Compactors

Table 5-23 ANOVA of Compaction for Different Field and SGC Compacted Cores

	<i>Sum of Squares</i>	<i>df</i>	<i>Mean Square</i>	<i>F</i>	<i>Sig.</i>
<i>Between Groups</i>	6.847	3	2.282	.710	.552
<i>Within Groups</i>	122.072	38	3.212		
<i>Total</i>	128.918	41			

Furthermore, a statistical test of the hypothesis that the field permeability coefficients measured with the NCAT permeameter for the compacted sections by the three different compactors are equal was conducted in SPSS statistical software. Figure 5-20 and Figure 5-21 respectively show the boxplot of the coefficients of field permeability and laboratory permeabilities of the field cores of the test sections compacted by the different compactors respectively. However, unlike compaction, the ANOVA indicates that there is a significant difference between the field permeability coefficients of the sections compacted by the three different field compactor types at a 5% level of significance as shown in Table 5-24. Table 5-25 is the Tukey HSD (Honestly Significant Difference) which indicates that AMIR compacted sections of Site 10 has a significantly different field permeability values from the oscillatory and the vibratory roller compacted sections. Similarly, the field permeability coefficients of the oscillatory and the vibratory roller compacted sections of Site 10 are not significantly different from each other. Details of the data ANOVA output can be found in Appendix F.

Figure 5-20 Field Section Permeabilities of the Three Different Field Compaction Technologies

Figure 5-21 Lab. Permeability of the Field Compacted and SGC Cores

Table 5-24 ANOVA of Field Permeability for Different Field Compactors

	<i>Sum of Squares</i>	<i>df</i>	<i>Mean Square</i>	<i>F</i>	<i>Sig.</i>
<i>Between Groups</i>	.000	2	.000	10.123	.000
<i>Within Groups</i>	.000	106	.000		
<i>Total</i>	.001	108			

Table 5-25 Tukey HSD Pair-Wise Field Permeability Comparison of differently Compacted Sections

<i>Roller Type</i>			<i>Mean Difference (I-J)</i>	<i>Sig.</i>
<i>Tukey HSD</i>	<i>AMIR</i>	<i>Oscillatory</i>	-0.0016	0.002
		<i>Vibratory</i>	-0.0022	0.000
	<i>Oscillatory</i>	<i>AMIR</i>	.0016*	0.002
		<i>Vibratory</i>	-0.0006	0.503
	<i>Vibratory</i>	<i>AMIR</i>	.0022*	0.000
		<i>Oscillatory</i>	0.0006	0.503

Figure 5-22 is the dispersion plot of the field and laboratory permeability of different field compactors, as well as the SGC, compacted cores. The AMIR field permeability is the closest to the laboratory permeability of its cores compared to the oscillatory and the vibratory compactors. Also, AMIR laboratory permeability is the closest to the laboratory permeability of the SGC compacted cores. Analysis of variance (ANOVA) results indicates that there was a significant difference between the laboratory permeability values of the cores extracted from the sections compacted by the three different types of field compaction methods and the SGC specimens at a 5% level of significance as shown in Table 5-26. Equally, Table 5-27 is the Tukey HSD pair-wise comparison of the laboratory permeability of the field cores compared to the SGC cores.

The table clearly shows that the laboratory permeability of the AMIR compacted cores is not significantly different from the laboratory permeability of the SGC Cores. On the other hand, the laboratory permeability of the oscillatory and the vibratory compacted cores is significantly different from the laboratory permeability of the SGC compacted cores.

Figure 5-22 Field and Laboratory Permeability of the Three Compactor Types

Table 5-26 ANOVA of Lab. Permeability for Different Field Compactors

	<i>Sum of Squares</i>	<i>df</i>	<i>Mean Square</i>	<i>F</i>	<i>Sig.</i>
Between Groups	.000	3	.000	10.288	.000
Within Groups	.000	119	.000		
Total	.000	122			

Table 5-27 Tukey HSD Pair-Wise Lab. Permeability Comparison of differently Compacted Cores

<i>Roller Type</i>			<i>Mean Difference (I-J)</i>	<i>Sig.</i>
<i>Tukey HSD</i>	<i>AMIR</i>	<i>Oscillatory</i>	-0.00047	0.370
		<i>SGC</i>	0.00050	0.312
		<i>Vibratory</i>	-.00115*	0.001
	<i>Oscillatory</i>	<i>AMIR</i>	0.00047	0.370
		<i>SGC</i>	.00097*	0.010
		<i>Vibratory</i>	-0.00069	0.124
	<i>SGC</i>	<i>AMIR</i>	-0.00050	0.312
		<i>Oscillatory</i>	-.00097*	0.010
		<i>Vibratory</i>	-.00166*	0.000
	<i>Vibratory</i>	<i>AMIR</i>	.00115*	0.001
		<i>Oscillatory</i>	0.00069	0.124
		<i>SGC</i>	.00166*	0.000

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

Proper and adequate compaction of asphalt pavement is a very important and critical construction process that would guarantee the performance and durability of asphalt pavements. While several philosophies in aspects of design, construction and quality control of asphalt pavements have changed in the past, field equipment with respect to compaction of asphalt equipment has not changed, that is the use of the rotary steel drum compactors. This is notwithstanding the fact that the primary goals of various design philosophies and their corresponding laboratory compaction methods are to select proper mix designs among other alternatives. This is usually based on applicable design criteria and to replicate asphalt pavement volumetric and mechanical properties that are obtainable in the field. This is the main reason why standard mix design procedures are based on their associated or corresponding laboratory method of compaction. However, proper simulation of field compaction using the laboratory methods to achieve similar asphalt pavement properties is hard if not impossible to come by. This is because the conditions of the laboratory and field compaction methods differ in so many ways.

This thesis has explored the influence of main field compaction equipment on asphalt pavement compaction and permeability in relation to asphalt pavement quality control. The major goal is to highlight the effects of construction processes on the resulting properties of asphalt concrete and to complement or improve the current system that overemphasises high density or relative compaction without consideration to the process and the equipment used in achieving it in the field. Hence, the research hypothesis that density or relative compaction of field compacted pavement is not a sufficient or a reliable indicator to be

used as the sole quality control criterion is tested and studied at the field scale. The following general and specific findings can thus be drawn based on the various field compaction trials using the two main-stream compaction technologies (vibratory and oscillatory compaction trains) and the AMIR single roller compaction technology.

- Field compaction equipment and its process of compaction are important factors that control and influence the resulting properties of asphalt concrete controlling for other factors.
- Based on the compaction and laboratory permeability of field recovered and SGC cores, it is safe to conclude that field compaction methods differ from the laboratory compaction methods.
- Findings in the literature showed that permeability, being one of the fundamental properties of asphalt pavements controls the durability, moisture susceptibility and long-term performance of asphalt concrete. Based on the results of this thesis; it is concluded that permeability is influenced or controlled by compaction equipment used in pavement compaction.
- That permeability of field compacted specimens does not depend only on the air voids of the specimen but also on the compaction process used which further lays credence to the notion of the inadequacy of using density alone as a quality control indicator.
- AMIR compacted sections yield asphalt pavement that has a significantly higher strength indicator based on the indirect tensile strength (ITS) compared to that of the vibratory train compacted sections at comparable air voids level. Therefore, it

is safe to infer that the effects of the steel drum and the associated roller-induced cracks may impair asphalt pavement strength characteristics.

- Also, based on the results of ITS and compaction on the bridge deck concrete, it could be deduced that high pavement strength characteristics are not necessarily associated with the high compaction level of asphalt concrete. More so, asphalt pavements could have high strength characteristics but with higher ageing and moisture damage propensities.
- There is no significant difference between the vibratory and oscillatory compaction equipment that uses rotary steel drum available to the asphalt paving industry based on compaction and permeability studies of this work.
- The AMIR compaction technology produced the closest asphalt pavement property between the field and laboratory permeability compared to the oscillatory and the vibratory compactors based on the measured laboratory permeability at a comparable air voids level.

The results of the linear regression model indicating the interrelationships of these major factors with permeability show that;

- Increasing relative compaction would generally reduce permeability in line with the general understating of compaction.
- Compacting on stiffer bases would increase the mean permeability of the asphalt pavement. However, using the AMIR compaction would reduce the mean permeability of the pavement compared to the steel rotary drum conventional compaction.

- In line with conventional wisdom, increasing the number of rollers passes during compaction would generally reduce asphalt pavement permeability.
- More importantly, AMIR compaction would reduce the mean permeability per unit air voids compared to rotary steel drum conventional compaction.
- Based on the data from the various project sites used in the case one study of this research, the outcome of the mixed modelling indicates that the measured field permeability does not significantly correlate or vary between various project locations (sites).

Information and results of the preceding sections on the measurement of field permeability for the Carleton Permeability Device using the developed methodology indicate the following:

- An affordable, accurate, reliable, and consistent methodology using the eTape sensor that could track water level changes has been developed especially for a comparison of two or more systems to aid quality control and assurance of asphalt pavements jobs in real-time.
- A method of intuitively characterizing a permeable surface based on water level-time slope has been devised and proposed.
- From the slope of the level-time trend line, the estimation of the permeability coefficient in one dimension has been developed and it agrees well with the laboratory permeability values of the Karol-warner permeameter.
- Field calibrations, trials, and implementation indicate the newly developed method of measuring permeability and its use in the new device can accurately measure field permeability without operator bias when comparing two or more systems.

- The application software accompanying the device (data acquisition and data processing) aids automatic data acquisition, book-keeping and analysis in a timely fashion, thus allowing ample time for corrections to be applied.

The major message of the foregoing results is that the asphalt pavement compaction method influences the properties based on compaction and permeability studies of this thesis. Also, finished asphalt concrete quality control assessment should not be based on density or compaction level alone. Hence, the inclusion of permeability testing as part of a quality control scheme is warranted. Information and results from this thesis indicate that the newly developed Carleton Permeability Device is reliable and has the capability to be used in the field evaluation of asphalt pavement permeability.

6.2 Recommendations and Future Research

On the basis of the findings of this study, the following recommendations are made.

- Methods of asphalt pavement quality control and job acceptance should look beyond the end-result criteria of “compaction” alone as being used currently especially in a cold climate. The inclusion of permeability is highly recommended to be added to the existing quality control protocol.
- The AMIR Compaction technology has proven to be a more efficient technology for field compaction that yields asphalt pavements with improved desired properties. Therefore, it is recommended that the AMIR compaction technology should be a benchmark for quality control and job acceptance for other compactors. This recommendation is supported by the results and findings by Chelliah (2019).
- Field permeability testing should be incorporated into asphalt pavement quality control and job acceptance as soon as possible given that permeability can be

directly and reliably be measured on-site without expensive coring with the newly developed Carleton Permeability Device.

- Supervising agencies and contractors should take cognizance of the effects of the various compaction methods on rigid surfaces and provide adjusted and improved acceptance criteria.
- Field implementation of the newly proposed device should look at increasing the capacity of the device to test multiple points simultaneously. This was envisaged by incorporating multiple sensor ports for the sensor and in the data acquisition application.

This research involved tripartite collaboration between the supervising agency, a local contractor, and an academic institution. In a situation like this, individual expectations may not always be met and encountering constraints may be inevitable. Therefore, the following recommendations are made for future work on this subject matter.

- Given that the field sites used in this study are contractor's projects; the mix design used in the study was mainly 12.5mm NMA based on the job specifications of the supervising agency. Subsequent research in this regard should seek to accommodate other mix designations. There were constraints in some sites where there was not enough time to collect sufficient data due to the contractor's time and costs. Future studies should make proper funding and allowances to enable more data acquisitions.
- Further studies should focus on the on-site in-situ non-destructive evaluation during compaction for the AMIR roller to improve the consistency of in-situ compaction monitoring.

- Future research should investigate the microscopic characteristics of the different roller compacted cores using imaging techniques. These microscopic characteristics could then be used to simulate ageing, moisture damage under different environmental conditions.
- Finally, future research should equally consider viscoelastoplastic damage characteristics of the different roller compacted mixtures at comparable air voids levels to provide insight into their mechanical behaviours.

References

- AASHTO T331 (2013). *Standard Test Method for Bulk Specific Gravity and Density of Compacted Asphalt Mixtures Using Automatic Vacuum Sealing Method*. American Association of State Highway Transport Officials, Washington D.C.
- Abd El Halim, O. A., and Bauer, G. E. (1985). Premature Failure of Asphalt Overlays at Time of Construction. *Roads and Transportation Association of Canada Conference*, 223-262.
- Abd El Halim, O.A., Phang, W., & El Gindy, M. (1988). Extending the service life of asphalt pavements through the prevention of construction cracks. *Transportation Research Record*, 1178, 1-8.
- Abd El Halim, O. A., Lau, D. T., Razaqpur, A. G., & Winterink, J. A. (1996). Utilization of the relative rigidity concept to predict the failure of pipe systems under explosive loads. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 33(8), A373. [https://doi.org/10.1016/S0148-9062\(97\)87543-2](https://doi.org/10.1016/S0148-9062(97)87543-2)
- Abd El Halim, O. A., Razaqpur, A. G., & El Kashef, A. H. (1994). Effects of construction cracks on the design of asphalt pavements. *Canadian Journal of Civil Engineering*, 21(3), 410–418.
- Abd El Halim, O. A. (1984). Experimental and Field Investigation of the Influence of Relative Rigidity on the Problem of Reflection Cracking. *Transportation Research Record*, 1060, 88-98.
- Abd El Halim, O. A. & Abdelzaher, M. (2006). Asphalt Multi-Integrated Rollers and Steel Drum Compactors. *Journal of the Transportation Research Board*, TRR 1967, 173–

180. <https://doi.org/10.3141/1967-17>

Abd El Halim, O.A., Pinder, F., Chelliah, A., R., Abdelalim, O. (2013). Reducing Maintenance and Rehabilitation Costs through the Use of AMIR Compaction. *Civil Engineering and Architecture*, 1(3), 51-60.

Abd El Halim, O. A., Said, D., & Mostafa, A. (2009). A Protection of the Environment Through the Prevention of Surface Cracking. *Open Civil Engineering Journal*, 3, 7–15.

Abd El Halim, O. A., Abd El Halim, O. A., Awadalla, M., & Adel Hassanin, M. (2015). Development of the Asphalt Multi-Integrated Roller Field and Experimental Studies. *Journal of Construction Engineering*, 2015, 1-7.

Abd El Halim, O. A. (1984). Experimental and Field Investigation of the Influence of Relative Rigidity on the Problem of Reflection Cracking. *Transportation Research Record*, 1060, 88-98.

Abdullah, W. S., Taleb, O. M., & Abu-sa'da, N. M. (1998). Influence of Aggregate Type and Gradation on Voids of Asphalt Concrete Pavements. *Journal of Materials in Civil Engineering*, 10(2), 76–85.

Airey, G. D. & Choi, Y. (2002). State of the Art Report on Moisture Sensitivity Test Methods for Bituminous Pavement Materials. *Road Materials and Pavement Design*, 3(4), 355-372. <https://doi.org/10.1080/14680629.2002.9689930>

Airey, G. D., and Collop, A. C. (2016). Mechanical and structural assessment of laboratory- and field-compacted asphalt mixtures. *International Journal of Pavement Engineering*, 17(1), 50-63.

Allen, D. L., Schultz, D. B., & Fleckenstein, J. L. (2001). *Development and Proposed*

- Implementation of a Field Permeability Test for Asphalt Concrete*. Research Report KTC-01-19/SPR216-00-1F, Kentucky Transportation Center, University of Kentucky, Lexington, Kentucky, 1-89.
- Anani, B. A., Balghunaim, F., and Saleh, H. S. (1989). Effects of Field Control of Filler Contents and Compaction on Asphalt Mix Properties. *Transportation Research Record*, 12-17, 29–37.
- ASTM D6931 (2007). *Standard Test Method for Indirect Tensile (IDT) Strength of Bituminous Mixtures*, ASTM International, West Conshohocken, PA.
- ASTM D1188 (2015). *Standard Test Method for Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Coated Samples*, ASTM International, West Conshohocken, PA.
- ASTM D2726 (2017). *Standard Test Method for Bulk Specific Gravity and Density of Non-Absorptive Compacted Asphalt Mixtures*, ASTM International, West Conshohocken, PA.
- ASTM D6752 (2017). *Standard Test Method for Bulk Specific Gravity and Density of Compacted Asphalt Mixtures Using Automatic Vacuum Sealing Method*, ASTM International, West Conshohocken, PA.
- ASTM D5084-16a (2016). *Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter*, ASTM International, West Conshohocken, PA.
- Awadalla, M. (2015). *Field and Laboratory Investigation of Asphalt Pavement Permeability*. Carleton University, Ottawa.
- Awadalla, M., AbdElHalim, O. A., Yasser, H., Imran, B., & Pinder, F. (2017). Field and

- laboratory permeability of asphalt concrete pavements. *Canadian Journal of Civil Engineering*, 44(January), 233–243.
- Bell, A., B., Ene, M., Smiley, W., & Schoeneberger, J., A. (2013). A Multilevel Model Primer Using Proc Mixed. *A Proceeding of SAS Global Forum Conference*. Cary, NC: SAS Institute Inc.
- Bhattacharjee, S., & Mallick, R. B. (2002). An Alternative Approach for the Determination of Bulk Specific Gravity and Permeability of Hot Mix Asphalt (HMA). *International Journal of Pavement Engineering*, 3(3), 143–152.
<https://doi.org/10.1080/1029843021000067782>
- Brown, E. R., Hainin, M. R., Cooley, A., & Hurley, G. (2004). *Relationships of Hma in-Place Air Voids, Lift Thickness, and Permeability. Volumes One through Four*. NCHRP Report 531. Project. Transportation Research Board, Washington DC.
Retrieved from <http://www.trb.org/Main/Public/Blurbs/155185.aspx>
- Caro, S., Masad, E., Bhasin, A., & Little, D. (2010). Coupled Micromechanical Model of Moisture-Induced Damage in Asphalt Mixtures. *Journal of Materials in Civil Engineering*, 22(4), 380–388. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000031](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000031)
- Caro, S., Masad, E., Bhasin, A., & Little, D. N. (2008a). Moisture susceptibility of asphalt mixtures, Part 1: Mechanisms. *International Journal of Pavement Engineering*, 9(2), 81–98. <https://doi.org/10.1080/10298430701792128>
- Caro, S., Masad, E., Bhasin, A., & Little, D. N. (2008b). Moisture susceptibility of asphalt mixtures, Part 2: characterization and modelling, 9(1), 99–114.
<https://doi.org/10.1080/10298430701792144>

- CBC News, (2017). *Pothole claims almost quadrupled since 2015*.
(<https://www.cbc.ca/news/canada/ottawa/pothole-claims-ottawa-city-2017-1.4428569>, Posted: Dec 04, 2017 5:00 AM ET, Last Updated: December 4, 2017, accessed December 16th 2019 at 10:43PM EST).
- Chen, J., Lin, K., & Young, S. (2004). Effects of Crack Width and Permeability on Moisture-Induced Damage of Pavements. *Journal of Materials in Civil Engineering*, 16(3), 276–282. [https://doi.org/10.1061/\(ASCE\)0899-1561\(2004\)16:3\(276\)](https://doi.org/10.1061/(ASCE)0899-1561(2004)16:3(276))
- Chen, C., Williams, R. C., Ahmed, E., T., Lee, H. D., & Scott, S. (2013). Quality control/quality assurance testing for longitudinal joint density and segregation of asphalt mixtures. *Construction and Building Materials*, 47,80-85.
<http://dx.doi.org/10.1016/j.conbuildmat.2013.05.007>
- Chen, J., Wang, H., & Zhu, H. (2017). Investigation of permeability of open-graded asphalt mixture considering effects of anisotropy and two-dimensional flow. *Construction and Building Materials*, 145, 318–325.
<https://doi.org/10.1016/j.conbuildmat.2017.04.028>
- Chen, L. M., Chen, J.W., Chen, T.H., Lecher, T., Davidson, P. C. (2019). Measurement of permeability and comparison of pavements. *MPDI Water*, 11 (3), 1-21.
- Chen, S., Adhikari, S., and You, Z. (2019). Relationship of coefficient of permeability, porosity, and air voids in fine-graded HMA. *Journal of Materials in Civil Engineering*, 31(1), 1-8.
- Chelliah, A., R. (2019). *Technical and Economic Development of Efficient Asphalt Multi-Integrated Compaction Technology*. Carleton University, Ottawa.
- Choubane, B., Page, G. C., and Musselman, J., A. (1997). *Florida Method of Test for*

- Measurement of Water Permeability of Compacted Asphalt Paving Mixtures.* Research Report FL/DOT/SMO/97-416, Florida Department of Transportation, 1-28.
- Choubane, B and Page, G. (1998). Investigation of Water Permeability of Coarse Graded Superpave Mixes. *Association of Asphalt Paving Technologist*, 67, 254-276.
- Christensen, D., & Bonaquist, R. F. (2015). Improved Practical Model for Permeability and Implications for the Design of High-Performance Hot-Mix Asphalt. *Transportation Research Record: Journal of the Transportation Research Board*, 2505(2505), 1–5. <https://doi.org/10.3141/2505-01>
- Coleri, E., Kayhanian, M., & Harvey, J. (2014). Permeability of Porous Friction Course Pavements. *Transportation Research Record: Journal of the Transportation Research Board*, 2456, 21–29. <https://doi.org/10.3141/2456-03>
- Cong, L., Zhang, Y., Xiao, F., & Wei, Q. (2016). Laboratory and field investigations of permeability and surface temperature of asphalt pavement by infrared thermal method. *Construction and Building Materials*, 113, 442–448. <https://doi.org/10.1016/j.conbuildmat.2016.03.078>
- Consuegra, A., Little, D. N., Von Quintus, H., Burati, James. (1989). Comparative evaluation of laboratory compaction devices based on their ability to produce mixtures with engineering properties similar to those produced in the field. *Transportation Research Record*, 1228,80-87.
- Cooley, L. A. (1999). *Permeability of Superpave Mixtures: Evaluation of Field Permeameters.* NCAT Report 99-01, National Center for Asphalt Technology, Auburn University, Alabama.

- Cooley, L., & Brown, E. (2000). Selection and Evaluation of Field Permeability Device for Asphalt Pavements. *Transportation Research Record*, 1723(1), 73–82. <https://doi.org/10.3141/1723-10>
- Cooley, L., Brown, E., & Maghsoodloo, S. (2001). Developing Critical Field Permeability and Pavement Density Values for Coarse-Graded Superpave Pavements. *Transportation Research Record*, 1761(1), 41–49. <https://doi.org/10.3141/1761-06>
- Cooley, L., & Maghsoodloo, S. (2002). Round-Robin Study for Field Permeability Test. *Transportation Research Record*, 1789(1), 25–35. <https://doi.org/10.3141/1789-03>
- CTV News, Ottawa (2019). *51-thousand potholes filled so far this year*. (<https://ottawa.ctvnews.ca/51-thousand-potholes-filled-so-far-this-year-1.4346311>, Published Thursday, March 21, 2019, 3:19PM EDT, Last Updated Thursday, March 21, 2019, 6:44 PM EDT, accessed 16th December 2019 at 10:40 PM EST)
- Dafalla, M., Shaker, A. A., Elkady, T., Al-Shamrani, M., & Dhowian, A. (2015). Effects of confining pressure and effective stress on hydraulic conductivity of sand-clay mixtures. *Arabian Journal of Geosciences*, 8(11), 9993–10001. <https://doi.org/10.1007/s12517-015-1925-1>
- Darban, A. K. (1993). *The Effect of Compaction Method On the Fatigue Life and Elasto-Plastic Properties of Asphalt Pavements*. Carleton University, Ottawa.
- Darcy, H. (1856). *The Public Fountains Of The City Of Dijon*. Kendall/Hunt Publishing Company, Dubuque, Iowa.
- Das, B. M. (2007). *Principles of Foundation Engineering, Sixth Edition*. Nelson, a Division of Thompson Canada Limited.
- Das, P. K., Baaj, H., Kringos, N., & Tighe, S. (2015). Coupling of oxidative ageing and

- moisture damage in asphalt mixtures. *Road Materials and Pavement Design*, 16(May), 265–279. <https://doi.org/10.1080/14680629.2015.1030835>.
- Ekse, M., & Zia, Z., T. (1953). Field Measurement of Air-Permeability for Control of Bituminous Mat Construction. *Proceedings of the Association of Asphalt Paving Technologists, Technical Sessions, 22*, (pp. 44-55).
- Ellis, W., & Schmidt, R. (1961). A Method for Measuring the Air Permeabilities of Asphalt. *ASTM Special Technical Publication, No 294(1)*, 85–91.
- Finn, F. N. and, & Epps, J. A. (1980). *Compaction of Hot Mix Asphalt Concrete*. Research Reports 214-21, Texas Transportation Institute, The Texas A&M University System College Station, Texas.
- Fleckenstein, L. J., Allen, D. L., & Schultz Jr, D. B. (2002). *Compaction at the Longitudinal Construction Joint in Asphalt Pavements*. Research Report KTC-02-10/SPR208-00-1F, University of Kentucky, Lexington. <https://doi.org/10.1016/j.jallcom.2009.03.047>
- Florida DOT (2004). *Florida Method of Test for Measurement of Water Permeability of Compacted Asphalt Paving Mixtures*. FM 5-565, Florida Department of Transportation.
- Gilson Inc. (2013). Operating Manual NCAT Asphalt Field Permeameter Kit. Retrieved from. <https://www.globalgilson.com/Content/Images/uploaded/pdf/product-manuals/manual-asphalt-field-permeameter.pdf?v=20190728155918337>
- Geller, M. (1984). Compaction Equipment for Asphalt Mixtures. *American Society of Testing and Materials, ASTM 829(F.T. Wagner Edition)*, 28–47.
- Gogula, A., Hossain, M., & Romanoschi, S. (2003). Correlation between the Laboratory

- and Field Permeability Values for the Superpave Pavements. *Proceedings of the 2003 Mid-Continent Transportation Research Symposium, Ames, Iowa*, (August 2003).
- Hainin, M. R., Yusoff, N. I. M., Mohd Satar, M. K. I., & Brown, E. R. (2013). The effect of lift thickness on permeability and the time available for compaction of hot mix asphalt pavement under tropical climate condition. *Construction and Building Materials*, 48, 315–324. <https://doi.org/10.1016/j.conbuildmat.2013.06.092>
- Hall, K. (2004). Comparison of Falling-Head and Constant-Head Techniques: Estimating Field Permeability of Hot-Mix Asphalt Pavements. *Transportation Research Record*, 1891(1), 23–31. <https://doi.org/10.3141/1891-04>
- Hall, K., Josue, C., & Hooi, N. (2000). Effects of Testing Time and Confining Pressure on Falling-Head Permeability Tests of Hot-Mix Asphalt Concrete. *Transportation Research Record*, 1723(1), 92–96. <https://doi.org/10.3141/1723-12>
- Hall, K., & Ng, H. (2001). Development of Void Pathway Test for Investigating Void Interconnectivity in Compacted Hot-Mix Asphalt Concrete. *Transportation Research Record*, 1767(1), 40–47. <https://doi.org/10.3141/1767-06>
- Harris, C., Wang, L., Druta, C., Tan, Y., Zhou, G., Zhu, T., & Cooley, L. (2011). Effect of Permeameter Size and Anisotropy on Measurements of Field Pavement Permeability. *Transportation Research Record: Journal of the Transportation Research Board*, 2209, 41–51. <https://doi.org/10.3141/2209-06>
- Harris, H. C. (2007). *Hot Mix Asphalt Permeability : Tester Size Effects and Anisotropy*. Virginia Polytechnic Institute and State University.
- Haveem, F. N. (1940). Gradation of Mineral Aggregates for dense-graded bituminous mixes. *Association of Asphalt Paving Technologists*, 11, 315-339.

- Huang, B., Raghavendra, A., & Mohammad, L. (1999). Fundamentals of Permeability in Asphalt Mixtures. *The Annual Meeting of the Association of Asphalt Paving Technologist*, (504).
- Hughes, C. S. (1989). *Compaction of Asphalt Pavement*. NCHRP Synthesis of Highway Practice 152, Transportation Research Board of the National Academies, Washington DC.
- Hveem, F N; Zube, E and Skog, J. (1959). Progress report on the Zaca-Wigmore Experimental Asphalt Test Project. In *Symposium on road and paving materials, 1959; ASTM Special Technical Publication No:277*. ASTM Special Technical Edition.
- Igboke, C., El Harake, T., Hassan, Y., Abd El Halim, A. E. H., & Goubran, R. (2018). Field and Laboratory Studies for the Determination of Highway Permeability. In *Canadian Technical Asphalt Association*, Regina, Saskatchewan, November 10-12, (pp. 171–187).
- Ingles, O. G. (1993). Discussion "Pavement Failures: Oversights, Omissions and Wishful Thinking, *Journal of performance of Constructed Facilities* 7(1), 74–74.
- IOWA, DoT (2005). *Comapcting Asphalt Concrete By the Marshal Method*. Matls. IM325, Iowa Department of Transportation.
- Kearney, J. E. (2006). Oscillatory Compaction of Hot-Mix Asphalt. In Recent Advances In Compaction Equipment, Including Intelligent Compaction (pp. 49-53). *Factors Affecting Compaction of Asphalt Pavements*. Transportation Research Circular E-C 105, Transportation Research Board, Washington DC.
- Kassem, E. A. (2008). *Compaction Effects on Uniformity, Moisture Diffusion, and*

Mechanical Properties of Asphalt Pavements. Texas A & M University, College Station.

Kandhal, P. S. and Mallick, R. B. (2007). Evaluation of Various Longitudinal Joint Construction Techniques for Airfield Pavements. In *FAA Worldwide Airport Technology Transfer Conference*. New Jersey, USA.

Kanitpong, K., Bahia, H., Russell, J., & Schmitt, R. (2005). Predicting Field Permeability from Testing Hot-Mix Asphalt Specimens Produced by Superpave Gyratory Compactor. *Transportation Research Record*, 1929(1), 52–58.
<https://doi.org/10.3141/1929-07>

Kanitpong, K., Benson, C., & Bahia, H. (2001). Hydraulic Conductivity (Permeability) of Laboratory-Compacted Asphalt Mixtures. *Transportation Research Record: Journal of the Transportation Research Board*, 1767(01), 25–32.
<https://doi.org/10.3141/1767-04>

Kayhanian, M., Anderson, D., Harvey, J.T., Jones, D., & Muhuntha, B. (2012). Permeability measurement and scan imaging to assess clogging of pervious concrete pavements in parking lots. *Journal of Environmental Management*, 95, 114–123.

Khan, Z. A., Al-Abdul Wahab, H. I., Asi, I., and Ramadhan, R. (1998). Comparative study of asphalt concrete laboratory compaction methods to simulate field compaction. *Construction and Building Materials*, 12(6), 373–384.

Król, J. B., Khan, R., & Collop, A. C. (2018). The study of the effect of internal structure on permeability of porous asphalt, *Road Materials and Pavement Design*, 19:4, 935–951, DOI: 10.1080/14680629.2017.1283355. Kutay, M., E., and Aydilek, A., H. (2007). *Dynamic Effects on Moisture Transport in Asphalt Concrete*. *Journal of Transportation Engineering*, 133(7), 406–414.

- Kutay, M., E., Aydilek, A., H., and Masad, E. (2007). Estimating Directional Permeability of Hot-Mix Asphalt by Numerical Simulation of Microscale Water Flow. *Transportation Research Record: Journal of Transportation Research Board*, 2001, 29-36
- Kutay, M., E., Ozturk, H., I., Abbas, A. R., and Hu, C. (2011). Comparison of 2D and 3D image-based aggregate morphological indices. *Internal Journal of Pavement Engineering*, 12(4), 421-431.
- Lees, G., & Katekhda, D. (1974). Prediction of Medium and High Speed Skid Resistance Values By Means of A Newly Developed Outflow Meter. In *Proceedings of the Association of Asphalt Paving Technologists, Technical Sessions*. (pp. 436–464).
- Lemon, B. (2011). *Intelligent Asphalt Compaction Analyzer*. Haskell Lemon Construction Company, Oklahoma City.
- Li, H., Kayhanian, M., and Harvey, J. T. (2013). Comparative field permeability measurement of permeable pavements using ASTM C1701 and NCAT permeameter methods. *Journal of Environmental Management*, 118, 144-152.
- Linden, N R Mahoney, J P and Jackson, N. C. (1989). Effect of Compaction on Asphalt Concrete Performance. *Transportation Research Record*, 1217, 20-28.
- Liu, P., Xu, H., Wang, D., Wang, C., Schulze, C., and Oeser, M. (2018). Comparison of mechanical responses of asphalt mixtures manufactured by different compaction methods. *Construction and Building Materials*, 162, 765-780.
- Mallick, R. B., Cooley, L. A., Teto, M., & Bradbury, R. (2001). Development of a Simple Test for Evaluation of In-Place Permeability of Asphalt Mixes. *International Journal of Pavement Engineering*, 2(2), 67–83. <https://doi.org/10.1080/10298430108901718>

- Mallick, R. B., Cooley, L. A., Teto, M. R., Bradbury, R. L., & Peabody, D. (2003). *An evaluation of factors affecting permeability of Superpave designed pavements*. NCAT Report 03-02, National Center for Asphalt Technology, Auburn University, Alabama.
- Mallick, R. B., & Daniel, J. S. (2006). Development and evaluation of a field permeameter as a longitudinal joint quality indicator. *International Journal of Pavement Engineering*, 7(1), 11–21. <https://doi.org/10.1080/10298430500501860>
- Mahmoud, E., Gates, L., Masad E., Erdogan, S., and Garboczi, E. (2010). Comprehensive Evaluation of AIMS Texture, Angularity, and Dimension Measurements. *Journal of Materials in Civil Engineering* 22 (4), 369-379.
- Masad, E., Jandhyala, V. K., Dasgupta N., Somadevan, N., and Shashidhar, N. (2002). Characterization of Air Void Distribution in Asphalt Mixes using X-ray Computed Tomography. *Journal of Materials in Civil Engineering* 14 (2), 122-129.
- Masad, E., Al-Omari, A., & Lytton, R. (2006). Simple Method for Predicting Laboratory and Field Permeability of Hot-Mix Asphalt. *Transportation Research Record*, 1970(1), 55–63. <https://doi.org/10.3141/1970-07>
- Masad, E., Scarpas, A. T., Rajagopal, K. R., Kassem, E., Koneru, S., Kasbergen, C., Kassem, E. (2015). Finite element modelling of field compaction of hot mix asphalt. Part II : Applications. *International Journal of Pavement Engineering*, 17(1), 24–38. <https://doi.org/10.1080/10298436.2013.863310>
- Maupin, G. W. (2000). *Investigation of Test Methods, Pavements, and Laboratory Design Related to Asphalt Permeability*. VTRC 00-R24, Virginia Department of Transportation, Charlottesville, Virginia.
- Maupin, G. W. (2010). Examination of an Implemented Asphalt Permeability

- Specification. VTRC 11-R7, Virginia Department of Transportation, Charlottesville, Virginia. <https://doi.org/10.1111/j.1467-9639.1991.tb00167.x>
- McKesson, C. L. (1949). Slippery Pavement-Causes and Treatments. In *Proceedings of the Association of Asphalt Paving Technologists, Technical Sessions, 18, 1-18*.
- McLaughlin, J. F and Goetz, W. H. (1955). Permeability, Void Content and Durability of Bituminous Concrete. *Materials and Construction, 34, 274-286*.
- Menard, J., & Croveti, J. (2006). Comparative Analysis of Field Permeability Testing of Compacted Hot-Mix Asphalt Pavements: Using Air and Water Permeameters. *Transportation Research Record, 1946(1)*, 147–156. <https://doi.org/10.3141/1946-17>
- Milone Technologies Inc. *Continuous Fluid Level Sensor PN-6573P-12* (<https://img1.wsimg.com/blobby/go/6e1bce17-f4fa-40c3-9d89-9bb7445697bb/downloads/Standard%20eTape%20Data%20Sheet.pdf>, accessed Dec. 27th, 2019).
- Miller, S.R., (2010). *Hot mix asphalt construction: towards a more professional approach*. Ph.D. Thesis. Construction management and engineering, University of Twente, Enschede, The Netherlands.
- Mostafa, A. (2005). *The Stripping Susceptibility of Airfield Asphalt Mixes: The Development of Guidelines for a Laboratory Test Method*. Carleton University, Ottawa.
- Mohamed, E. H., Abd El Halim, O.A., and Kennepohl, G. J. (1993). Assessment of the influence of compaction method on asphalt concrete resistance to moisture damage. *Construction and Building Materials, 7(3), 149-156*.
- MTO(2010). *OPSS 310: Construction Specifications for Hot Mix Asphalt, pp. 21*.

- MTO (2019). *Development of In-Situ Permeability Apparatus for Hot Mix Asphalt (HMA) Pavements- Phase II*. Ministry of Transportation Materials Engineering and Research Office, Toronto, Ontario.
- MTO LS-262 (1999). *Method of Test for Bulk Relative Density of Compacted Bituminous Mixtures*. Ministry of Transportation Materials Engineering and Research Office, Toronto, Ontario.
- MTO LS-297 (2011). *Method of Test for the Determination of Indirect Tensile Strength of Expanded Asphalt Mixes*. Ministry of Transportation Materials Engineering and Research Office, Toronto, Ontario.
- MTO LS-264 (2012). *Method of Test for Theoretical Maximum Relative Density of Bituminous Paving Mixtures*. Ministry of Transportation Materials Engineering and Research Office, Toronto, Ontario.
- Noel, B. R. (1977). Compacting Heavy Duty Highway Pavement. In *Proceedings, Association of Asphalt Paving Technologists*, 46, 309-375.
- Nose, Y. (2006). Vibratory Pneumatic Tire Roller. In *Recent Advances In Compaction Equipment, Including Intelligent Compaction* (pp. 54-68). Factors Affecting Compaction of Asphalt Pavements. Transportation Research Circular E-C 105, Transportation Research Board, Washington DC.
- OHMPA (2013). *The ABCs of Longitudinal Joints*. Ontario Hot Mix Producers Association, Mississauga, Ontario. Retrieved from <http://www.onasphalt.org/files/Publications/ABCs%20of%20Longitudinal%20Joints.pdf>

- Omar, L. G., & Abd El Halim, O. A. (2018). Improving the Skid Resistance and Surface Texture of Asphalt Pavement Using AMIR Compactor Technology. *Civil Engineering Research Journal*, 6(2), 9.
<https://doi.org/10.19080/CERJ.2018.06.555682>
- Omar, L. G., Chelliah, A., Abd El Halim, O. A. E. H., & Yasser, H. (2018). Improved Surface Texture of Asphalt Roads Using Single-Roller Compaction. In *63rd Proceeding of the Canadian Technical Asphalt Association* (pp. 147–170).
- Owusu-ababio, S., Hall, O., & Schmitt, R. L. (2009). A Framework for Performance-Based Permeability and Density Acceptance Criteria for HMA Pavements in Wisconsin. *Mid-Continent Transportation Research Symposium* (pp. 1–13).
- Parker, C. F. (1960). Steel-Tired Rollers. *Highway Research Board Bulletin*, 246, 1–40.
- Plati, C., Georgiou, P., and Loizos, A., (2016). Influence of different roller compaction modes on asphalt mix performance. *International Journal of Pavement Engineering*, 17(1), 64-70.
- Poulikakos, L., D., Pittet, M., Arnaud, L., Junod, A., Gubler, R., Simond, E., Partl, M. and Dumont, A.-G. (2006). *Mechanical Properties of Porous Asphalt, Recommendations for Standardization*. Rapport OFROU 1185. VSS Vereinigung Schweizerischer Strassenfachleute, Switzerland. Retrieved from <https://infoscience.epfl.ch/record/121491/files/VSS1999-280-v.%2010.p>.
- Prowell, B. D., & Dudley, M. C. (2002). Evaluation of measurement techniques for asphalt pavement density and permeability. *Journal of the Transportation Research Board*, TRR 1789(02), 36–45. <https://doi.org/10.3141/1789-04>
- Ratner, B. (2009). The Correlation Coefficient: Its values range between +1/-1, or do they?.

- Journal of Targeting, Measurement and Analysis for Marketing*, 17(2), 139-142.
- Retzer, N. (2008). *Permeability Research With the Romus Air Permeameter*. Report No. CDOT-2008-5, Colorado Department of Transportation, Denver.
- Rollings, B. R. S., & Rollings, M. P. (1992). Pavement failures: Oversights, Omissions and Wishful Thinking. *Journal of performance of Constructed Facilities*, 5(4), 271–286.
- Russell, J., Bahia, H. U., Kanitpong, K., Croveti, J., & Schmitt, R. (2005). *Effect of Pavement Thickness on Superpave Mix Permeability and Density*. Research Study 0092-02-14, Wisconsin Department of Transportation, Madison.
- Said D., Abd EI Halim, O. A., Pais, J. C. (2008). Study of the causes and remedies of premature Surface Cracking of Asphalt Pavements. EPAM 3-3rd *European Pavement and Asset Management Conference*, Coimbra, Portugal, 7-9 July.
- Schmitt, R., Croveti, J., & Cooley, A. L. (2007). Development of In-Place Permeability Criteria for HMA Pavement in Wisconsin. SPR # 0092-06-02, Wisconsin Department of Transport, Madison.
- Standiford, D. L., Graul, R. A., & Lenke, L. R. (1985). *Permeability Equipment for Porous Friction Surfaces*. DOT/FAA/ PM-85/31, US Department of Transportation, Federal Aviation Administration, Washington.
- Tay, R. (2017). Correlation, Variance Inflation and Multicollinearity in Regression Model. *Journal of the East Asian Society of Transportation Studies*, 12, 2006-2015.
- Tarefder, R. A., & Ahmad, M. (2016). Effect of compaction procedure on air void structure of asphalt concrete. *Measurement: Journal of the International Measurement Confederation*, 90, 151–157. <https://doi.org/10.1016/j.measurement.2016.04.054>
- Tarefder, R. A., & Ahmad, M. (2017). Evaluation of pore structure and its influence on

- permeability and moisture damage in asphalt concrete. *International Journal of Pavement Engineering*, 18(3), 274–283.
<https://doi.org/10.1080/10298436.2015.1065995>
- Tarefder, R. A., & Ahmad, M. (2015). Evaluating the Relationship between Permeability and Moisture Damage of Asphalt Concrete Pavements. *Materials in Civil Engineering*, 27(5), 1–10. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0001129](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001129).
- Transportation Research Circular E-C105. (2006). *Factors Affecting Compaction of Asphalt Pavements*. Transportation Research Board, Washington DC.
<https://doi.org/10.17226/23282>
- Vardanega, P. J., & Waters, T. J. (2011). Analysis of Asphalt Concrete Permeability Data Using Representative Pore Size. *Journal of Materials in Civil Engineering*, 23(2), 169–176. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000151](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000151)
- Vardanega, P. J. (2014). State of the Art: Permeability of Asphalt Concrete. *Journal of Materials in Civil Engineering*, 26(1), 54–64.
[https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000748](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000748)
- Wang, H., Wang, Z., Bennert, T., & Weed, R. (2016). Specification Limits and Pay Adjustment for Longitudinal Joint Density of Asphalt Pavements. *Transportation Research Record: Journal of the Transportation Research Board*, 2573, 98–106.
<https://doi.org/10.3141/2573-12>
- Wang, W., Wang, L., Xiong, H., & Luo, R. (2019). A review and perspective for research on moisture damage in asphalt pavement induced by dynamic pore water pressure. *Construction and Building Materials*, 204, 631–642.
- Washington, DoT (2005). Factors affecting HMA Permeability. *Washington State*

- Department of Transportation. Retrieved from <https://www.wsdot.wa.gov/NR/rdonlyres/BB595DA7-99F9-4D73-A4B4-844FFDB5A784/0/FactorsAffectingHMAPermeabilityTN.pdf>
- White, D. T. (1975). Porous Friction Surface Course. Interim Report S-75-12. US Army Engineers Waterways Experiment Station, Vicksburg, Mississippi.
- White, T. D. (1976). Field Performance of a Porous Friction Course. FAA-RD-74-3B, US Department of Transportation, Federal Aviation Administration, Washington DC.
- Williams, C. (2015). *Premature Asphalt Concrete Pavement Cracking*. SPR 734 (FHWA-OR-RD-15-16), Oregon Department of Transportation, Salem. Retrieved from http://www.oregon.gov/ODOT/TD/TP_RES/
- Williams, G. S. (2007). Sample Size Requirements for Field Permeability Measurements of Hot-Mix Asphalt Pavements. *Transportation Research Record*, 2001(1), 56–62.
- Williams, R. C. (2009). *Early Permeability Test for Asphalt Acceptance*. RI07-053, Centre for Transportation Research and Education, Iowa State University, Ames.
- Williams, S. (2011). Density, Permeability, Infiltration, and Absorption Used to Assess Quality of Hot-Mix Asphalt Longitudinal Joints. *Transportation Research Record: Journal of the Transportation Research Board*, 2228, 120–127. <https://doi.org/10.3141/2228-14>
- Wistuba, M.P. (2016). The German segmented steel roller compaction method - State-of-the-art report. *International Journal of Pavement Engineering*, 17(1), 81-86.
- Wolfinger, R., and Chnag, M. (1995). Comparing SAS GLM and Mixed Procedures for Repeated Measures. *SAS Institute Inc. NC*.
- Wu, C., Gumpertz, M., L., & Boos, D., D.(2001). Comparison of GEE, MINQUE, ML,

- and REML Estimating Equations for Normally Distributed Data. *Journal of the American Statistical Association* 55 (2), 125-130.
- Yan, Y., Zaniewski, J. P., & Hernando, D. (2016). Development of a predictive model to estimate permeability of dense-graded asphalt mixture based on volumetrics. *Construction and Building Materials*, 126, 426-433.
<https://doi.org/10.1016/j.conbuildmat.2016.09.071>
- Zhao, Y., Wang, X., Jiang, J., and Zhou, L. (2019). Characterization of interconnectivity, size distribution and uniformity of air voids in porous asphalt concrete using X-ray CT scanning images. *Journal of Construction and Building Materials*, 213, 182-193.
- Zube, E. (1962). Compaction Studies of Asphalt Concrete Pavement as Related to the Water Permeability Test. In *41st Annual Meeting of the Highway Research Board*, January 8-12, 358 (pp. 12-37).

Appendices

Appendix A Schematic of Permeameters in the Literature

Figure A.1 Schematic Diagram of The Dynamic Air Flow Meter (Standiford et al., 1985)

Figure A. 2 Schematic Diagram of The Static Air Permeameter (Standiford et al., 1985)

Figure A. 3 ASTM Static Air Permeability Meter (Standiford et al., 1985)

Figure A. 4 Schematic Diagram of The Dynamic Pavement Permeameter (Standiford et al., 1985)

Figure A. 5 Schematic Diagram of The Birmingham University Outflow Meter (Lees & Katekhda, 1974)

Figure A. 6 Schematic Diagram of WES Permeability Apparatus (Standiford et al., 1985)

Appendix B Test and Calibration Data for the eTape Sensor

Table B. 1 Sensor Output Calibration Data for the Carol-Warner (Florida) Device

<i>S/N</i>	<i>Head (mV)</i>	<i>Head (cm)</i>	<i>S/N</i>	<i>Head (mV)</i>	<i>Head (cm)</i>	<i>S/N</i>	<i>Head (mV)</i>	<i>Head (cm)</i>	<i>S/N</i>	<i>Head (mV)</i>	<i>Head (cm)</i>
1	1000	77	27	40	51	53	142	53	79	862	73
2	955	76	28	0	50.4	54	106	52	80	833	72
3	923	75	29	1000	77	55	42	51	81	804	71
4	889	74	30	956	76	56	0	50.4	82	770	70
5	854	73	31	920	75	57	674	68	83	723	69
6	831	72	32	891	74	58	626	66	84	670	68
7	809	71	33	860	73	59	595	65	85	640	67
8	776	70	34	833	72	60	565	64	86	620	66
9	725	69	35	804	71	61	530	63	87	594	65
10	672	68	36	771	70	62	500	62	88	560	64
11	652	67	37	725	69	63	452	61	89	530	63
12	624	66	38	671	68	64	429	60	90	490	62
13	594	65	39	641	67	65	377	59	91	450	61
14	564	64	40	624	66	66	356	58	92	431	60
15	529	63	41	695	65	67	309	57	93	380	59
16	512	62	42	563	64	68	285	56	94	355	58
17	453	61	43	531	63	69	263	55	95	306	57
18	423	60	44	501	62	70	196	54	96	284	56
19	382	59	45	449	61	71	129	53	97	252	55
20	354	58	46	425	60	72	105	52	98	209	54
21	320	57	47	378	59	73	38	51	99	136	53
22	285	56	48	356	58	74	0	50.4	100	100	52

23	265	55	49	320	57	75	1000	77	101	35	51
24	205	54	50	283	56	76	956	76	102	0	50.4
25	137	53	51	263	55	77	930	75	103	320	57
26	104	52	52	202	54	78	890	74	104	289	56

Table B. 2 Sensor Output Calibration Data for any use with Constant Cross-Sectional Area

<i>S/N</i>	<i>Head (mV)</i>	<i>Tape (in)</i>	<i>S/N</i>	<i>Head (mV)</i>	<i>Tape (in)</i>	<i>S/N</i>	<i>Head (mV)</i>	<i>Tape (in)</i>
1	954	8	29	860	10	57	994	11.5
2	603	7	30	835	9.5	58	947	11
3	527	6	31	784	9	59	901	10.5
4	483	5.5	32	728	8.5	60	999	12
5	434	5	33	681	8	61	947	11.5
6	342	4	34	635	7.5	62	901	10.5
7	292	3.5	35	606	7	63	999	12
8	266	3	36	575	6.5	64	996	11.6
9	195	2.5	37	977	11.5	65	945	11
10	130	2	38	945	11	66	900	10.5
11	1	0	39	901	10.5	67	861	10
12	899	10.5	40	868	10	68	840	9.5
13	863	10	41	836	9.5	69	784	9
14	783	9	42	988	11.5	70	681	8
15	671	8	43	943	11	71	638	7.5
16	628	7.5	44	901	10.5	72	617	7
17	604	7	45	864	10	73	532	6
18	527	6	46	993	11.5	74	450	5
19	441	5	47	943	11	75	346	4
20	377	4.5	48	901	10.5	76	274	3
21	346	4	49	0	1	77	136	2
22	999	12	50	0	1	78	997	11.5
23	997	11.5	51	139	2	79	1000	12
24	957	11	52	79	1.5	80	997	11
25	998	12	53	0	1	81	946	11
26	997	11.5	54	999	12	82	901	10.5
27	949	11	55	996	11.5	83	998	12
28	1000	11.5	56	949	11	84	267	3

Table B. 3 Comparison of Differently Measured Lab. Permeabilities for the AMIR Compacted Cores

<i>Air Voids (%)</i>	<i>Sloped Permeability (cm/secs)</i>	<i>Florida Lab Permeability (cm/sec)</i>	<i>Measured Permeability (cm/sec)</i>
6.54	3.50E-03	3.5E-03	3.50E-03
6.54	3.34E-03	2.92E-03	3.39E-03
6.54	3.38E-03	2.87E-03	3.39E-03
6.54	3.23E-03	2.83E-03	3.26E-03
6.90	1.08E-05	1.07E-05	1.08E-05
6.90	0.00E+00	0.00E+00	0.00E+00
7.08	3.96E-04	3.80E-04	4.11E-04
7.08	3.30E-04	3.05E-04	3.35E-04
7.08	2.97E-04	2.80E-04	2.98E-04
7.08	2.83E-04	2.82E-04	2.84E-04
7.08	2.86E-04	2.72E-04	2.84E-04
7.17	8.30E-05	8.33E-05	8.30E-05
7.17	7.95E-05	7.97E-05	7.95E-05
7.40	6.6E-05	6.36E-05	6.6E-05
7.40	6.6E-05	6.31E-05	6.6E-05
7.76	3.5E-05	3.812E-05	3.5E-05
8.28	1.69E-03	1.66E-03	1.7E-03
8.28	1.63E-03	1.60E-03	1.6E-03
8.28	1.55E-03	1.58E-03	1.5E-03
8.28	1.53E-03	1.51E-03	1.5E-03
8.67	1.18E-03	1.18E-03	1.18E-03
8.67	1.24E-03	1.14E-03	1.25E-03
8.67	1.20E-03	1.08E-03	1.20E-03
8.67	1.18E-03	1.15E-03	1.19E-03
9.74	2.07E-03	1.95E-03	2.09E-03
9.74	2.07E-03	1.82E-03	2.02E-03
9.74	1.80E-03	1.67E-03	1.85E-03
9.74	1.60E-03	1.54E-03	1.63E-03
9.93	8.52E-04	8.03E-04	8.71E-04
9.93	8.02E-04	7.57E-04	8.41E-04
9.93	7.36E-04	7.22E-04	7.57E-04
9.93	7.11E-04	6.91E-04	7.34E-04
9.93	6.45E-04	6.57E-04	6.83E-04
10.07	3.25E-03	3.18E-03	3.20E-03
10.07	3.14E-03	3.18E-03	3.18E-03
10.07	3.11E-03	3.18E-03	3.18E-03
10.07	3.08E-03	3.02E-03	3.11E-03

Table B. 4 Comparison of Differently Measured Lab. Permeabilities for the Vibratory Train Compacted Cores

<i>Air Voids (%)</i>	<i>Sloped Permeability (cm/secs)</i>	<i>Florida Lab Permeability (cm/sec)</i>	<i>Measured Permeability (cm/sec)</i>
6.19	1.05E-04	1.00E-04	1.06E-04
6.19	7.98E-05	8.01E-05	7.98E-05
8.17	1.15E-03	1.07E-03	1.12E-03
8.17	1.10E-03	1.07E-03	1.10E-03
8.17	1.01E-03	9.85E-04	9.87E-04
8.17	8.91E-04	8.83E-04	8.81E-04
9.25	2.69E-04	2.54E-04	2.79E-04
9.25	2.58E-04	2.33E-04	2.63E-04
9.25	2.46E-04	2.23E-04	2.51E-04
9.25	2.46E-04	2.16E-04	2.47E-04
10.52	3.07E-03	3.07E-03	3.00E-03
10.52	2.78E-03	2.66E-03	2.68E-03
10.52	2.14E-03	2.20E-03	2.29E-03
10.52	1.72E-03	1.84E-03	1.75E-03
10.52	1.57E-03	1.53E-03	1.59E-03
10.52	3.50E-03	3.44E-03	3.56E-03
10.52	3.35E-03	3.23E-03	3.29E-03
10.52	3.37E-03	3.23E-03	3.41E-03
10.52	3.29E-03	3.13E-03	3.44E-03
11.50	3.84E-03	3.64E-03	3.79E-03
11.50	3.58E-03	3.64E-03	3.70E-03
11.50	3.44E-03	3.43E-03	3.55E-03
11.50	3.29E-03	3.24E-03	3.37E-03
11.75	5.3E-03	5.24E-03	5.56E-03
11.75	5.4E-03	5.24E-03	5.42E-03
11.75	5.4E-03	5.24E-03	5.39E-03
11.75	5.5E-03	5.24E-03	5.39E-03

Figure B. 2 Equality Plot of Sensor Permeability Calibration Data for Vibratory Train Compacted Cores at Site 10

Table B. 5 Comparison of Differently Measured Lab. Permeabilities for the Oscillatory Train Compacted Cores

<i>Air Voids (%)</i>	<i>Sloped Permeability (cm/secs)</i>	<i>Florida Lab Permeability (cm/sec)</i>	<i>Measured Permeability (cm/sec)</i>
7.763	7.66E-04	7.56E-04	7.71E-04
7.763	7.49E-04	7.48E-04	7.48E-04
7.763	7.56E-04	7.34E-04	7.46E-04
7.763	7.48E-04	7.46E-04	7.51E-04
8.16	2.18E-03	2.20E-03	2.41E-03
8.16	2.16E-03	2.20E-03	2.25E-03
8.16	1.48E-03	1.59E-03	1.44E-03
8.16	1.14E-03	1.26E-03	1.17E-03
8.16	9.69E-04	1.00E-03	9.56E-04
8.16	8.28E-04	8.44E-04	8.22E-04
8.16	2.16E-03	2.0E-03	2.21E-03
8.16	1.99E-03	1.9E-03	1.99E-03
8.16	1.74E-03	1.7E-03	1.74E-03
8.16	1.53E-03	1.5E-03	1.56E-03
8.42	3.31E-03	3.23E-03	3.31E-03
8.42	3.11E-03	3.11E-03	3.12E-03
8.42	3.33E-03	3.11E-03	3.19E-03
8.42	3.32E-03	3.01E-03	3.43E-03
9.33	1.91E-03	1.81E-03	1.88E-03
9.33	1.66E-03	1.63E-03	1.68E-03
9.33	1.45E-03	1.36E-03	1.46E-03
9.33	1.17E-03	1.17E-03	1.18E-03
9.97	1.24E-03	1.11E-03	1.11E-03
9.97	1.10E-03	1.08E-03	1.08E-03
9.97	1.05E-03	1.04E-03	1.04E-03
9.97	1.11E-03	1.04E-03	1.04E-03
12.08	2.85E-03	2.80E-03	2.98E-03
12.08	2.84E-03	2.71E-03	2.79E-03
12.08	2.60E-03	2.63E-03	2.51E-03
12.08	2.63E-03	2.49E-03	2.64E-03

Figure B. 3 Equality Plot of Sensor Permeability Calibration Data for Oscillatory Train Compacted Cores at Site 10

Appendix C Case 1 Field Compaction and Permeability Data

Table C. 1 Case 1: Field Compaction and Permeability Data

<i>Comp</i>	<i>Va</i>	<i>K</i>	<i>ITS</i>	<i>Pavt</i>	<i>Rol</i>	<i>Passes</i>	<i>Thick</i>	<i>Site No</i>
93.33	6.67	4.33E-04	147.31	0	0	22	50	Site 1
93.34	6.66	3.43E-04	127.74	0	0	22	50	Site 1
93.39	6.61	1.48E-04	173.76	0	0	22	50	Site 1
91.46	8.54	1.04E-03	141.50	0	0	22	50	Site 1
91.72	8.28	1.01E-03	166.75	0	0	22	50	Site 1
92.00	8.00	1.82E-04	146.29	0	0	22	50	Site 1
93.95	6.05	7.07E-04	219.67	0	0	22	50	Site 1
94.12	5.88	6.08E-04	119.10	0	0	22	50	Site 1
90.47	9.53	1.40E-03	164.08	0	0	22	50	Site 1
93.94	6.06	1.24E-04	81.55	0	0	22	50	Site 1
96.09	3.91	5.83E-04	235.97	0	1	8	50	Site 1
97.65	2.35	4.77E-04	312.95	0	1	8	50	Site 1
94.62	5.38	2.64E-04	186.96	0	1	8	50	Site 1
94.71	5.29	1.11E-04	188.62	0	1	8	50	Site 1
93.69	6.31	1.61E-03	278.53	0	1	8	50	Site 1
94.57	5.43	5.89E-04	213.86	0	1	8	50	Site 1
92.47	7.53	5.30E-04	241.18	0	1	8	50	Site 1
97.73	2.27	1.51E-04	252.54	0	1	8	50	Site 1
93.47	6.53	5.48E-04	169.66	0	1	8	50	Site 1
96.63	3.37	4.43E-04	239.81	0	1	8	50	Site 1
91.28	8.72	9.21E-03	168.33	0	1	8	50	Site 1
89.27	10.73	1.11E-02	133.67	0	1	8	50	Site 1
87.65	12.35	2.51E-03	95.62	0	1	8	50	Site 1
94.55	5.45	1.75E-02	389.03	0	1	8	50	Site 1
86.18	13.82	1.53E-02	419.08	0	1	8	50	Site 1
94.76	5.24	1.35E-02	434.56	0	1	8	50	Site 1
96.87	3.13	4.91E-03	582.67	0	1	8	50	Site 1
98.10	1.90	7.32E-03	612.24	0	1	8	50	Site 1
95.71	4.29	4.66E-03	501.21	0	1	8	50	Site 1
96.75	3.25	8.54E-04	551.80	0	1	8	50	Site 1
97.56	2.44	9.94E-03	490.13	0	1	8	50	Site 1
97.81	2.19	9.94E-03	534.25	0	1	8	50	Site 1
96.00	4.00	8.76E-03	285.57	0	1	8	50	Site 1
98.23	1.77	3.14E-03	286.42	0	1	8	50	Site 1

95.52	4.48	1.59E-03	174.93	0	1	8	50	Site 1
93.33	6.67	7.44E-04	53.43	0	0	22	50	Site 2
93.41	6.59	6.12E-04	54.68	0	0	22	50	Site 2
93.32	6.68	3.36E-04	57.58	0	0	22	50	Site 2
94.11	5.89	4.79E-04	52.58	0	0	22	50	Site 2
93.93	6.07	3.58E-04	44.40	0	0	22	50	Site 2
93.20	6.80	1.89E-04	47.41	0	0	22	50	Site 2
92.10	7.90	1.57E-04	42.25	0	0	22	50	Site 2
92.01	7.99	1.30E-04	42.68	0	0	22	50	Site 2
93.90	6.10	4.81E-05	60.91	0	0	22	50	Site 2
93.42	6.58	1.09E-04	49.14	0	0	22	50	Site 2
93.90	6.10	5.16E-04	78.69	0	1	8	50	Site 2
92.60	7.40	4.50E-04	73.18	0	1	8	50	Site 2
94.10	5.90	2.76E-04	77.44	0	1	8	50	Site 2
93.70	6.30	1.65E-04	78.27	0	1	8	50	Site 2
93.12	6.88	4.03E-04	56.75	0	1	8	50	Site 2
93.11	6.89	3.29E-04	62.16	0	1	8	50	Site 2
94.13	5.87	2.71E-04	67.85	0	1	8	50	Site 2
93.60	6.40	1.58E-04	69.18	0	1	8	50	Site 2
93.40	6.60	5.74E-05	62.16	0	1	8	50	Site 2
92.30	7.70	1.37E-04	65.18	0	1	8	50	Site 2
93.56	6.44	2.81E-04	359.32	0	0	22	50	Site 3
93.12	6.88	2.26E-03	412.57	0	0	22	50	Site 3
91.68	8.32	8.95E-04	347.62	0	0	22	50	Site 3
93.28	6.72	6.51E-03	437.73	0	0	22	50	Site 3
94.72	5.28	9.85E-04	453.88	0	0	22	50	Site 3
94.60	5.40	2.75E-04	453.06	0	0	22	50	Site 3
93.48	6.52	3.09E-04	423.66	0	0	22	50	Site 3
94.12	5.88	2.28E-04	465.94	0	0	22	50	Site 3
94.24	5.76	1.38E-03	493.49	0	0	22	50	Site 3
93.36	6.64	1.34E-03	367.04	0	0	22	50	Site 3
93.20	6.80	3.21E-04	438.86	0	0	22	50	Site 3
93.52	6.48	2.63E-04	361.44	0	0	22	50	Site 3
93.76	6.24	3.35E-04	351.43	0	0	22	50	Site 3
94.44	5.56	2.51E-04	464.79	0	0	22	50	Site 3
93.52	6.48	2.83E-04	372.68	0	0	22	50	Site 3
92.94	7.06	2.34E-03	252.72	0	0	22	50	Site 4
94.67	5.33	8.34E-04	246.86	0	0	22	50	Site 4
94.27	5.73	1.01E-03	257.00	0	0	22	50	Site 4
91.72	8.28	2.76E-03	276.16	0	0	22	50	Site 4
92.77	7.23	2.49E-03	265.63	0	0	22	50	Site 4

93.54	6.46	2.09E-03	313.67	0	0	22	50	Site 4
94.67	5.33	5.21E-03	193.52	0	0	22	50	Site 4
92.73	7.27	2.69E-03	273.84	0	0	22	50	Site 4
95.40	4.60	6.77E-04	435.97	0	0	22	50	Site 4
93.26	6.74	1.31E-03	305.76	0	0	22	50	Site 4
94.83	5.17	5.29E-04	362.80	0	0	22	50	Site 4
95.76	4.24	2.05E-03	313.30	0	0	22	50	Site 4
93.87	6.13	2.14E-03	463.02	0	0	22	50	Site 5
92.95	7.05	7.39E-04	452.52	0	0	22	50	Site 5
93.75	6.25	7.77E-03	400.88	0	0	22	50	Site 5
92.15	7.85	1.19E-03	312.46	0	0	22	50	Site 5
90.91	9.09	1.29E-03	298.90	0	0	22	50	Site 5
90.99	9.01	3.29E-03	281.76	0	0	22	50	Site 5
89.91	10.09	1.62E-03	263.58	0	0	22	50	Site 5
92.31	7.69	7.35E-04	398.70	0	0	22	50	Site 5
91.11	8.89	1.55E-03	315.16	0	0	22	50	Site 5
88.35	11.65	4.52E-03	250.79	0	0	22	50	Site 5
91.71	8.29	1.49E-03	460.04	0	0	22	50	Site 5
91.91	8.09	9.59E-04	367.37	0	0	22	50	Site 5
91.47	8.53	8.89E-04	283.27	0	0	22	50	Site 5
90.91	9.09	1.88E-03	343.47	0	0	22	50	Site 5
89.83	10.17	1.77E-03	273.37	0	0	22	50	Site 5
91.32	8.68	1.02E-02	302.84	1	0	22	50	Site 6
90.14	9.86	7.30E-03	254.01	1	0	22	50	Site 6
90.77	9.23	7.88E-03	272.99	1	0	22	50	Site 6
89.68	10.32	1.62E-02	245.54	1	0	22	50	Site 6
88.19	11.81	1.93E-02	636.44	1	0	22	50	Site 7
88.57	11.43	4.53E-02	659.33	1	0	22	50	Site 7
89.16	10.84	3.98E-02	390.86	1	0	22	50	Site 7
86.25	13.75	1.97E-02	257.58	1	0	22	50	Site 7
89.43	10.57	3.74E-02	453.62	1	0	22	50	Site 7
93.16	6.84	1.54E-02	1024.21	1	1	8	50	Site 7
92.25	7.75	7.25E-03	723.42	1	1	8	50	Site 7
88.41	11.59	1.85E-04	803.20	1	1	8	50	Site 7
88.90	11.10	4.11E-03	475.38	1	1	8	50	Site 7
90.40	9.60	2.53E-02	562.95	1	1	8	50	Site 7
90.07	9.93	2.22E-02	721.00	1	1	8	50	Site 7
90.63	9.37	1.20E-02	70.77	0	0	22	50	Site 8
91.80	8.20	2.14E-03	117.40	0	0	22	50	Site 8
91.45	8.55	1.02E-02	93.15	0	0	22	50	Site 8
91.80	8.20	3.14E-03	112.94	0	0	22	50	Site 8

91.18	8.82	1.76E-03	86.87	0	0	22	50	Site 8
90.51	9.49	1.45E-02	111.75	0	0	22	50	Site 8
90.39	9.61	1.94E-03	120.67	0	0	22	50	Site 8
87.73	12.27	4.40E-04	72.99	0	0	22	50	Site 8
89.37	10.63	2.61E-03	90.02	0	0	22	50	Site 8
90.98	9.02	1.24E-02	106.31	0	0	22	50	Site 8
92.08	7.92	2.50E-04	137.88	0	1	8	50	Site 8
90.90	9.10	5.66E-04	76.87	0	1	8	50	Site 8
94.16	5.84	1.79E-03	99.66	0	1	8	50	Site 8
91.96	8.04	4.72E-03	100.17	0	1	8	50	Site 8
92.43	7.57	2.10E-03	100.31	0	1	8	50	Site 8
92.31	7.69	3.77E-03	75.76	0	1	8	50	Site 8
90.39	9.61	1.57E-03	99.74	0	1	8	50	Site 8
86.94	13.06	1.66E-04	79.69	0	1	8	50	Site 8
92.47	7.53	8.24E-05	112.88	0	1	8	50	Site 8
92.71	7.29	5.63E-04	95.39	0	1	8	50	Site 8
91.35	8.65	4.55E-03		0	0	12	65	Site 9
90.24	9.76	5.02E-03		0	0	12	70	Site 9
88.00	12.00	1.18E-02		0	0	12	58	Site 9
89.15	10.85	8.88E-03		0	0	12	55	Site 9
89.09	10.91	9.40E-03		0	0	12	54	Site 9
89.75	10.25	1.28E-02		0	0	18	42	Site 9
90.15	9.85	9.90E-03		0	0	18	50	Site 9
92.41	7.59	2.50E-03		0	0	18	55	Site 9
90.69	9.31	5.71E-03		0	0	24	54	Site 9
92.59	7.41	3.26E-03		0	0	24	57	Site 9
91.82	8.18	4.09E-03		0	0	24	66	Site 9
93.86	6.14	1.31E-03		0	0	24	65	Site 9
93.78	6.22	1.71E-03		0	0	24	85	Site 9
94.53	5.47	9.01E-04		0	0	24	87	Site 9
92.23	7.77	3.91E-03		0	0	24	63	Site 9
89.52	10.48	3.31E-03		0	1	4	55	Site 9
88.34	11.66	5.84E-03		0	1	4	58	Site 9
88.49	11.51	5.11E-03		0	1	4	56	Site 9
89.34	10.66	4.50E-03		0	1	4	57	Site 9
89.53	10.47	5.07E-03		0	1	4	56	Site 9
89.20	10.80	2.92E-03		0	1	6	56	Site 9
89.69	10.31	3.07E-03		0	1	6	55	Site 9
90.94	9.06	2.46E-03		0	1	6	64	Site 9
88.64	11.36	1.05E-03		0	1	8	56	Site 9
91.76	8.24	3.71E-03		0	1	8	65	Site 9

92.21	7.79	1.55E-03	0	1	8	67	Site 9
91.55	8.45	1.25E-03	0	1	8	70	Site 9
92.10	7.90	7.94E-04	0	1	8	95	Site 9
93.88	6.12	4.27E-04	0	1	8	95	Site 9
91.02	8.98	2.44E-03	0	1	8	62	Site 9

Table C. 2 Covariance Parameters: Random Intercept and Slope with Fixed Effects Variables as Random Variables

<i>Cov Parm</i>	<i>Subject</i>	<i>Estimate</i>	<i>Standard Error</i>	<i>Z Value</i>	<i>Pr > Z</i>
<i>Intercept</i>	<i>Site_No</i>	0	.	.	.
<i>Comp</i>	<i>Site_No</i>	0	.	.	.
<i>Pavt</i>	<i>Site_No</i>	0.000210	0.000304	0.69	0.2452
<i>Passes</i>	<i>Site_No</i>	0	0	.	.
<i>VaRol</i>	<i>Site_No</i>	0	0	.	.
<i>PavtRol</i>	<i>Site_No</i>	0.000231	17424	0.00	0.5000
<i>Rol</i>	<i>Site_No</i>	0	.	.	.
<i>Residual</i>		0.000016	0	8.45	<.0001

Note: Converged with Non-Definite Hessian

Table C. 3 Fit Statistics: Random Intercept and Slope with Fixed Effects Variables as Random Variables

<i>-2 Res Log Likelihood</i>	-1234.2
<i>AIC (Smaller is Better)</i>	-1224.2
<i>AICC (Smaller is Better)</i>	-1223.8
<i>BIC (Smaller is Better)</i>	-1223.2

Note: Converged with Non-Definite Hessian

Table C. 4 Solution of Fixed Effects: Random Intercept and Slope with Fixed Effects Variables as Random Variables

<i>Effect</i>	<i>Estimate</i>	<i>Standard Error</i>	<i>DF</i>	<i>t Value</i>	<i>Pr > t </i>	<i>Alpha</i>
<i>Intercept</i>	0.06370	0.01977	104	3.22	0.0017	0.05
<i>Comp</i>	-0.00057	0.000198	103	-2.90	0.0046	0.05
<i>Pavt</i>	0.01724	0.01038	1.01	1.66	0.3439	0.05
<i>Passes</i>	-0.00037	0.000115	125	-3.24	0.0015	0.05
<i>VaRol</i>	-0.00071	0.000273	11.6	-2.61	0.0235	0.05
<i>PavtRol</i>	-0.01511	0.1187	1	-0.13	0.9194	0.05

Table C. 5 Covariance Parameters: Random Intercept and Slope with Pavt and Rol as Random Variables

<i>Cov Parm</i>	<i>Subject</i>	<i>Estimate</i>	<i>Standard Error</i>	<i>Z Value</i>	<i>Pr > Z</i>
<i>Intercept</i>	<i>Site_No</i>	0	0	.	.
<i>Pavt</i>	<i>Site_No</i>	0.000204	0.000295	0.69	0.2442
<i>Rol</i>	<i>Site_No</i>	0	0	0.89	0.1876
<i>Residual</i>		0.000017	0	8.44	<.0001

Table C. 6 Fit Statistics: Random Intercept and Slope with Pavt and Rol as Random Variables

<i>-2 Res Log Likelihood</i>	-1231.8
<i>AIC (Smaller is Better)</i>	-1223.8
<i>AICC (Smaller is Better)</i>	-1223.5
<i>BIC (Smaller is Better)</i>	-1223.0

Table C. 7 Solution of Fixed Effects: Random Intercept and Slope with Pavt and Rol as Random Variables

<i>Effect</i>	<i>Estimate</i>	<i>Standard Error</i>	<i>DF</i>	<i>t Value</i>	<i>Pr > t </i>	<i>Alpha</i>
<i>Intercept</i>	0.07300	0.02121	45.7	3.44	0.0012	0.05
<i>Comp</i>	-0.00069	0.000217	44.1	-3.18	0.0027	0.05
<i>Pavt</i>	0.01689	0.01025	1.01	1.65	0.3452	0.05
<i>Passes</i>	-0.00032	0.000132	58.7	-2.39	0.0198	0.05
<i>VaRol</i>	-0.00055	0.000235	76.1	-2.34	0.0221	0.05
<i>PavtRol</i>	-0.01742	0.003685	8.52	-4.73	0.0013	0.05

Table C. 8 Covariance Parameters: Random Slopes Only Model

<i>Cov Parm</i>	<i>Subject</i>	<i>Estimate</i>	<i>Standard Error</i>	<i>Z Value</i>	<i>Pr > Z</i>
<i>Pavt</i>	<i>Site_No</i>	0.000209	0.000302	0.69	0.2446
<i>Passes</i>	<i>Site_No</i>	0	0	.	.
<i>VaRol</i>	<i>Site_No</i>	0	0	.	.
<i>PavtRol</i>	<i>Site_No</i>	0.000194	0	.	.
<i>Rol</i>	<i>Site_No</i>	0	.	.	.
<i>Residual</i>		0.000016	0	8.45	<.0001

Note: Converged with Non-Definite Hessian

Table C. 9 Fit Statistics: Random Slopes Only Model

<i>-2 Res Log Likelihood</i>	-1234.2
<i>AIC (Smaller is Better)</i>	-1224.2
<i>AICC (Smaller is Better)</i>	-1223.8
<i>BIC (Smaller is Better)</i>	-1223.2

Note: Converged with Non-Definite Hessian

Table C. 10 Solution of Fixed Effects: Random Slopes Only Model

<i>Effect</i>	<i>Estimate</i>	<i>Standard Error</i>	<i>DF</i>	<i>t Value</i>	<i>Pr > t </i>	<i>Alpha</i>
<i>Intercept</i>	0.06370	0.01977	104	3.22	0.0017	0.05
<i>Comp</i>	-0.00057	0.000198	103	-2.90	0.0046	0.05
<i>Pavt</i>	0.01724	0.01037	1.01	1.66	0.3424	0.05
<i>Passes</i>	-0.00037	0.000115	125	-3.24	0.0015	0.05
<i>VaRol</i>	-0.00071	0.000273	11.6	-2.61	0.0235	0.05
<i>PavtRol</i>	-0.01511	0.01472	156	-1.03	0.3062	0.05

Note: Converged with Non-Definite Hessian

Table C. 11 Covariance Parameters: Random Pavt and Rol without Intercept

<i>Cov Parm</i>	<i>Subject</i>	<i>Estimate</i>	<i>Standard Error</i>	<i>Z Value</i>	<i>Pr > Z</i>
<i>Pavt</i>	<i>Site_No</i>	0.000203	0.000293	0.69	0.2439
<i>Rol</i>	<i>Site_No</i>	0	0	0.95	0.1711
<i>Residual</i>		0.000017	0	8.72	<.0001

Table C. 12 Fit Statistics: Random Pavt and Rol without Intercept

<i>-2 Res Log Likelihood</i>	-1231.6
<i>AIC (Smaller is Better)</i>	-1225.6
<i>AICC (Smaller is Better)</i>	-1225.5
<i>BIC (Smaller is Better)</i>	-1225.0

Table C. 13 Solution of Fixed Effects: Random Pavt and Rol without Intercept

<i>Effect</i>	<i>Estimate</i>	<i>Standard Error</i>	<i>DF</i>	<i>t Value</i>	<i>Pr > t </i>	<i>Alpha</i>
<i>Intercept</i>	0.07614	0.01888	142	4.03	<.0001	0.05
<i>Comp</i>	-0.00072	0.000194	119	-3.70	0.0003	0.05
<i>Pavt</i>	0.01681	0.01021	1.01	1.65	0.3456	0.05
<i>Passes</i>	-0.00033	0.000121	105	-2.75	0.0070	0.05
<i>VaRol</i>	-0.00058	0.000223	107	-2.58	0.0114	0.05
<i>PavtRol</i>	-0.01735	0.003588	10.8	-4.83	0.0005	0.05

Appendix D SAS Scripts for the OLS and Mixed Models

Title 'Field Permeability Model Proc Reg (OLS)'

```
libname Work.Projectdata222;
Proc means data=Work.Projectdata222 maxdec=2;
ods excel file="P:\ProjectData\Triple-Table.xls";
Title 'Data Summary Statistics';
ods nonproctitle;
ods excel close;
run
By Rol;
run;
/****Raw Data Screening,Diagnostics and Explorations****/
Proc reg data=Work.Projectdata222;
Model K=Comp Va Gmm Gmb ITS Pavt Rol Thick Passes ComTem PGH PGL Ac RAP
Dust PAN VMA S4 S8 VFA Site_1 Site_2 Site_3 Site_4 Site_5 Site_6 Site_7 Site_8
Site_9/ stb tol vif collino int rsquare r influence;
ods excel file="P:\ProjectData\Multiple-Table.xls";
Title 'Collinearity Statistics1';
ods nonproctitle;
run;
ods excel close
run;
/****Centering of some key variables for multicollinearity and diagnostics****/
data work.centre;
set Work.Projectdata222;
Va=(Va-2*2.3756856);/****standardized air voids****/
Gmm=Gmm-2.5249242;
Gmb=Gmb-2.3398030;
comp=Comp-92.6853030;
ITS=ITS-267.2263636;
run;
Proc means data=Work.centre;
Proc reg data=Work.centre;
Model K=Comp ITS Pavt Rol Thick Passes Site_1 Site_2 Site_3 Site_4 Site_5 Site_6
Site_7 Site_8 Site_9/Stb tol vif collino int rsquare r influence;
ods excel file="P:\ProjectData\Multiple-Table.xls";
Title 'Collinearity Statistics2';
ods nonproctitle;
run;
ods excel close;
run;
/****checking for power relationship between K and Va or cVa****/
Data Work.Power;
```

```

Set work.centre;
sqVa=Va*Va;
cbVa=Va*Va*Va;
Proc reg data=Work.Power;
Model K=sqVa cbVa;
run;
/****Checking for interaction between Va and other independent variables****/
Data Work.Interaction;
Set Work.Power;
VaGmm=Va*Gmm;
VaGmb=Va*Gmb;
VaITS=Va*ITS;
VaPavt=Va*pavt;
VaRol=Va*Rol;
RolPas=Rol*Passes;
ThickVa=Thick*Va;
ThickRol=Thick*Rol;
CompRol=Comp*Rol;
PavtRol=Pavt*Rol;
PavtRolVa=Pavt*Rol*Va;
PavtRolComp=Pavt*Rol*Comp;
sqVaRol=sqVa*Rol;
sqVaRolPavt=sqVa*Rol*Pavt;
sqVaPavtRol=Va*Va*Pavt*Rol;
cbVaPavtRol=Va*Va*Va*Pavt*Rol;
run;
Proc reg data=Work.Interaction;
Model K=Comp Va Gmm Gmb ITS Pavt Rol Thick Passes VaGmm VaGmb VaITS
VaPavt VaRol CompRol PavtRol ComTem PGH PGL Ac RAP Dust PAN VFA VMA S4
S8 Site_1 Site_2 Site_3 Site_4 Site_5 Site_6 Site_7 Site_8 Site_9/stb clb partial Scorr2
tol vif selection = rsquare best = 10 cp tol vif;
run;
/****Computation of Correlation Matrix****/
Data Work.CorrMatrix;
Set Work.Interaction;
run;
proc corr data=Work.CorrMatrix;
var K Comp Va Passes Pavt ITS Thick Rol ComTem PGH PGL Ac RAP Dust PAN VFA
VMA S4 S8;
ods excel file="P:\ProjectData\Triple-Table.xls";
Title 'Correlation Matrix';
ods nonproctitle;
run;
ods excel close;
run;
/***** Final Model Selection*****/

```

```

Data Work.Final;
Set Work.CorrMatrix;
run;
Proc Reg Data=Work.Final;
Model K=Comp Pavt Passes VaRol PavtRol sqVaRolPavt Site_2 Site_7/stb tol vif;
ods excel file="P:\ProjectData\Single-Table.xls";
Title 'Regression Statistics';
ods nonproctitle;
run;
ods excel close;
run;
/***** Select final model below Final Model for the Paper*****/

```

Title 'Field Permeability Proc Mixed Model'

```
libname Work.Projectdata222;
run;
Data Work.Interaction;
Set Work.ProjectData222;
VaGmm=Va*Gmm;
VaGmb=Va*Gmb;
VaITS=Va*ITS;
VaPavt=Va*pavt;
VaRol=Va*Rol;
RolPas=Rol*Passes;
ThickVa=Thick*Va;
ThickRol=Thick*Rol;
CompRol=Comp*Rol;
PavtRol=Pavt*Rol;
PavtRolVa=Pavt*Rol*Va;
PavtRolComp=Pavt*Rol*Comp;
SqVaRolPavt=Va*Va*Rol*Pavt;
run;
Proc Mixed Data=Work.Interaction covtest noelprint IC method=reml;
Class Site_No;
Model K=Comp Pavt Passes VaRol PavtRol/ solution CL DDFM=KR HTYPE=3
outputm=plots;
Random Intercept Comp Pavt Passes VaRol PavtRol Rol/ Subject=Site_No solution
type=vc;
ods graphics on;
ods excel file="P:\ProjectData\Single-Table.xls";
Title 'MM Output';
ods nonproctitle;
run;
ods excel close;
run;
ods output FitStatistics=Fitstat;
run;
```

Appendix E Case 2 Compaction and Permeability Data

Table E. 1 Case 2: Site 10 Compaction and Roller Data

<i>Gmb</i>	<i>Va (%)</i>	<i>Compaction (%)</i>	<i>Remarks</i>	<i>Compactor</i>
2.25	9.93	90.07	<i>Wearing</i>	<i>AMIR</i>
2.29	8.28	91.72	<i>Wearing</i>	<i>AMIR</i>
2.26	9.74	90.26	<i>Wearing</i>	<i>AMIR</i>
2.32	7.40	92.60	<i>Wearing</i>	<i>AMIR</i>
2.32	7.17	92.83	<i>Wearing</i>	<i>AMIR</i>
2.33	6.90	93.10	<i>Wearing</i>	<i>AMIR</i>
2.28	8.67	91.33	<i>Wearing</i>	<i>AMIR</i>
2.25	10.10	89.90	<i>Wearing</i>	<i>AMIR</i>
2.31	7.76	92.24	<i>Wearing</i>	<i>AMIR</i>
2.25	10.07	89.93	<i>Wearing</i>	<i>AMIR</i>
2.32	7.08	92.92	<i>Wearing</i>	<i>AMIR</i>
2.27	9.33	90.67	<i>Binder</i>	<i>AMIR</i>
2.32	7.05	92.95	<i>Binder</i>	<i>AMIR</i>
2.23	10.75	89.25	<i>Binder</i>	<i>AMIR</i>
2.21	11.75	88.25	<i>Binder</i>	<i>AMIR</i>
2.31	7.76	92.24	<i>Wearing</i>	<i>Oscillatory</i>
2.27	9.33	90.67	<i>Wearing</i>	<i>Oscillatory</i>
2.20	12.08	87.92	<i>Wearing</i>	<i>Oscillatory</i>
2.30	8.16	91.84	<i>Wearing</i>	<i>Oscillatory</i>
2.25	9.97	90.03	<i>Wearing</i>	<i>Oscillatory</i>
2.26	9.68	90.32	<i>Wearing</i>	<i>Oscillatory</i>
2.34	6.41	93.59	<i>Binder</i>	<i>Oscillatory</i>
2.30	8.08	91.92	<i>Binder</i>	<i>Oscillatory</i>
2.19	12.43	87.57	<i>Binder</i>	<i>Oscillatory</i>
2.35	5.98	94.02	<i>Binder</i>	<i>Oscillatory</i>
2.25	10.17	89.83	<i>Binder</i>	<i>Oscillatory</i>
2.29	8.42	91.58	<i>Binder</i>	<i>Oscillatory</i>
2.35	6.19	93.81	<i>Wearing</i>	<i>Vibratory</i>
2.21	11.50	88.50	<i>Wearing</i>	<i>Vibratory</i>
2.27	9.25	90.75	<i>Wearing</i>	<i>Vibratory</i>
2.30	8.17	91.83	<i>Wearing</i>	<i>Vibratory</i>
2.24	10.52	89.48	<i>Wearing</i>	<i>Vibratory</i>
2.21	11.75	88.25	<i>Wearing</i>	<i>Vibratory</i>

Table E. 2 Superpave Gyratory Compacted Samples from Site 10 Field Mix

<i>Gmb</i>	<i>Va (%)</i>	<i>Compaction (%)</i>	<i>Compactor</i>
2.35	6.01	93.99	SGC
2.34	6.52	93.48	SGC
2.34	6.63	93.37	SGC
2.33	6.97	93.03	SGC
2.27	9.22	90.78	SGC
2.27	9.30	90.70	SGC
2.26	9.50	90.50	SGC
2.25	9.93	90.07	SGC
2.25	10.10	89.90	SGC

Table E. 3 Descriptive Statistics of Compaction of All Cores

<i>Descriptives</i>			
	<i>N</i>	<i>Mean</i>	<i>Std. Deviation</i>
<i>AMIR</i>	15	91.20	1.55
<i>Oscillatory</i>	12	90.96	1.98
<i>SGC</i>	9	91.76	1.66
<i>Vibratory</i>	6	90.44	2.14
<i>Total</i>	42	91.14	1.77

Table E. 4 Levene Test of Homogeneity of Variances of All Compacted Cores

		<i>Levene Statistic</i>	<i>df1</i>	<i>df2</i>	<i>Sig.</i>
<i>Compaction (%)</i>	<i>Based on Mean</i>	.305	3	38	.822
	<i>Based on Median</i>	.228	3	38	.876
	<i>Based on Median and with adjusted df</i>	.228	3	32.673	.876
		2			
		8			
	<i>Based on trimmed mean</i>	.309	3	38	.819

Table E. 5 Tukey HSD Pair-Wise Field of Comparison of differently Compacted Cores

		<i>Multiple Comparisons</i>		
<i>Compactor Type</i>			<i>Mean Difference (I-J)</i>	<i>Sig.</i>
Tukey HSD	<i>AMIR</i>	<i>Oscillatory</i>	0.24	0.986
		<i>SGC</i>	-0.56	0.882
		<i>Vibratory</i>	0.77	0.813
	<i>Oscillatory</i>	<i>AMIR</i>	-0.24	0.986
		<i>SGC</i>	-0.8	0.746
		<i>Vibratory</i>	0.53	0.936
	<i>SGC</i>	<i>AMIR</i>	0.56	0.882
		<i>Oscillatory</i>	0.8	0.746
		<i>Vibratory</i>	1.32	0.508
	<i>Vibratory</i>	<i>AMIR</i>	-0.77	0.813
		<i>Oscillatory</i>	-0.53	0.936
		<i>SGC</i>	-1.32	0.508

Figure E. 1 Mean Plot of all Differently Compacted Cores

Table E. 6 Case 2: Site 10 Field Permeability for the Different Roller Compacted Sections

Compactor Type	Field Permeability (cm/secs)	4-NCAT Tier	Remarks
<i>Oscillatory</i>	2.13E-03	1	Binder Course
<i>Oscillatory</i>	2.16E-03	2	Binder Course
<i>Oscillatory</i>	2.16E-03	3	Binder Course
<i>Oscillatory</i>	1.09E-03	1	Binder Course
<i>Oscillatory</i>	9.40E-04	2	Binder Course
<i>Oscillatory</i>	4.16E-03	3	Binder Course
<i>Oscillatory</i>	1.94E-03	1	Binder Course
<i>Oscillatory</i>	1.09E-03	2	Binder Course
<i>Oscillatory</i>	1.44E-03	3	Binder Course
<i>Oscillatory</i>	1.36E-03	1	Binder Course
<i>Oscillatory</i>	9.40E-04	2	Binder Course
<i>Oscillatory</i>	4.08E-04	3	Binder Course
<i>Oscillatory</i>	4.53E-03	1	Binder Course
<i>Oscillatory</i>	4.16E-03	2	Binder Course
<i>Oscillatory</i>	3.67E-03	3	Binder Course
<i>Oscillatory</i>	2.09E-03	1	Wearing Course
<i>Oscillatory</i>	1.86E-03	2	Wearing Course
<i>Oscillatory</i>	2.87E-03	1	Wearing Course
<i>Oscillatory</i>	2.81E-03	2	Wearing Course
<i>Oscillatory</i>	2.71E-03	3	Wearing Course
<i>Oscillatory</i>	2.89E-03	1	Wearing Course
<i>Oscillatory</i>	2.69E-03	2	Wearing Course
<i>Oscillatory</i>	3.27E-03	3	Wearing Course
<i>Oscillatory</i>	1.30E-02	1	Wearing Course
<i>Oscillatory</i>	1.04E-02	2	Wearing Course
<i>Oscillatory</i>	9.62E-03	3	Wearing Course
<i>Oscillatory</i>	3.02E-03	1	Wearing Course
<i>Oscillatory</i>	2.12E-03	2	Wearing Course
<i>Oscillatory</i>	1.83E-03	3	Wearing Course
<i>Oscillatory</i>	1.31E-03	1	Wearing Course
<i>Oscillatory</i>	1.11E-03	2	Wearing Course
<i>Oscillatory</i>	1.15E-03	3	Wearing Course
<i>Oscillatory</i>	2.01E-03	1	Wearing Course
<i>Oscillatory</i>	1.63E-03	2	Wearing Course
<i>Oscillatory</i>	1.76E-03	3	Wearing Course
<i>Oscillatory</i>	2.74E-03	1	Wearing Course
<i>Oscillatory</i>	2.09E-03	2	Wearing Course
<i>Oscillatory</i>	1.86E-03	3	Wearing Course

Oscillatory	2.73E-03	1	<i>Wearing Course</i>
Oscillatory	2.21E-03	2	<i>Wearing Course</i>
Oscillatory	2.35E-03	3	<i>Wearing Course</i>
AMIR	9.13E-04	1	<i>Binder Course</i>
AMIR	7.95E-04	2	<i>Binder Course</i>
AMIR	1.36E-03	1	<i>Binder Course</i>
AMIR	1.35E-03	2	<i>Binder Course</i>
AMIR	1.24E-03	3	<i>Binder Course</i>
AMIR	1.09E-04	1	<i>Wearing Course</i>
AMIR	5.36E-04	2	<i>Wearing Course</i>
AMIR	6.80E-04	1	<i>Wearing Course</i>
AMIR	7.26E-04	2	<i>Wearing Course</i>
AMIR	1.24E-03	1	<i>Wearing Course</i>
AMIR	1.09E-03	2	<i>Wearing Course</i>
AMIR	1.13E-03	3	<i>Wearing Course</i>
AMIR	3.02E-03	1	<i>Wearing Course</i>
AMIR	3.03E-03	2	<i>Wearing Course</i>
AMIR	1.24E-03	1	<i>Wearing Course</i>
AMIR	1.05E-03	2	<i>Wearing Course</i>
AMIR	9.86E-04	3	<i>Wearing Course</i>
AMIR	1.53E-03	1	<i>Wearing Course</i>
AMIR	1.43E-03	2	<i>Wearing Course</i>
AMIR	1.68E-03	3	<i>Wearing Course</i>
AMIR	1.37E-03	1	<i>Wearing Course</i>
AMIR	1.46E-03	2	<i>Wearing Course</i>
AMIR	1.51E-03	3	<i>Wearing Course</i>
AMIR	2.39E-04	1	<i>Wearing Course</i>
AMIR	2.05E-04	2	<i>Wearing Course</i>
AMIR	2.10E-03	1	<i>Wearing Course</i>
AMIR	1.68E-03	2	<i>Wearing Course</i>
AMIR	1.54E-03	3	<i>Wearing Course</i>
AMIR	4.96E-04	1	<i>Wearing Course</i>
AMIR	4.57E-04	2	<i>Wearing Course</i>
AMIR	1.19E-03	1	<i>Wearing Course</i>
AMIR	1.04E-03	2	<i>Wearing Course</i>
AMIR	1.21E-03	3	<i>Wearing Course</i>
AMIR	6.69E-05	1	<i>Wearing Course</i>
AMIR	3.88E-03	1	<i>Wearing Course</i>
AMIR	4.08E-03	2	<i>Wearing Course</i>
AMIR	3.77E-03	3	<i>Wearing Course</i>
AMIR	7.79E-04	1	<i>Wearing Course</i>
AMIR	4.43E-04	2	<i>Wearing Course</i>

<i>AMIR</i>	5.13E-04	1	<i>Wearing Course</i>
<i>AMIR</i>	3.97E-04	2	<i>Wearing Course</i>
<i>AMIR</i>	1.43E-03	1	<i>Wearing Course</i>
<i>AMIR</i>	1.09E-03	2	<i>Wearing Course</i>
<i>AMIR</i>	1.02E-03	3	<i>Wearing Course</i>
<i>AMIR</i>	3.28E-04	1	<i>Wearing Course</i>
<i>AMIR</i>	2.44E-04	2	<i>Wearing Course</i>
<i>Vibratory</i>	9.06E-03	1	<i>Wearing Course</i>
<i>Vibratory</i>	6.76E-03	2	<i>Wearing Course</i>
<i>Vibratory</i>	7.01E-03	3	<i>Wearing Course</i>
<i>Vibratory</i>	9.56E-03	4	<i>Wearing Course</i>
<i>Vibratory</i>	1.94E-03	1	<i>Wearing Course</i>
<i>Vibratory</i>	1.65E-03	2	<i>Wearing Course</i>
<i>Vibratory</i>	1.72E-03	3	<i>Wearing Course</i>
<i>Vibratory</i>	2.47E-03	1	<i>Wearing Course</i>
<i>Vibratory</i>	1.86E-03	2	<i>Wearing Course</i>
<i>Vibratory</i>	1.54E-03	3	<i>Wearing Course</i>
<i>Vibratory</i>	1.09E-03	1	<i>Wearing Course</i>
<i>Vibratory</i>	1.11E-03	2	<i>Wearing Course</i>
<i>Vibratory</i>	1.04E-03	3	<i>Wearing Course</i>
<i>Vibratory</i>	9.06E-03	1	<i>Wearing Course</i>
<i>Vibratory</i>	5.40E-03	2	<i>Wearing Course</i>
<i>Vibratory</i>	4.97E-03	3	<i>Wearing Course</i>
<i>Vibratory</i>	2.98E-03	4	<i>Wearing Course</i>
<i>Vibratory</i>	2.27E-03	1	<i>Wearing Course</i>
<i>Vibratory</i>	1.93E-03	2	<i>Wearing Course</i>
<i>Vibratory</i>	1.86E-03	3	<i>Wearing Course</i>
<i>Vibratory</i>	4.85E-04	1	<i>Wearing Course</i>
<i>Vibratory</i>	5.43E-04	2	<i>Wearing Course</i>

Table E. 7 Descriptive Statistics of All Field Permeability Values

	<i>Descriptives</i>		
	<i>N</i>	<i>Mean</i>	<i>Std. Deviation</i>
<i>AMIR</i>	46	0.0013	0.00095
<i>Oscillatory</i>	41	0.0028	0.00253
<i>Vibratory</i>	22	0.0035	0.00298
<i>Total</i>	109	0.0023	0.00231

Table E. 8 Levene's Test of Homogeneity of Variances of Field Permeability Values

	<i>Levene Statistic</i>	<i>df1</i>	<i>df2</i>	<i>Sig.</i>
<i>Based on Mean</i>	11.844	2	106	.000
<i>Based on Median</i>	4.890	2	106	.009
<i>Based on Median and with adjusted df</i>	4.890	2	67.957	.010
<i>Based on trimmed mean</i>	9.927	2	106	.000

Table E. 9 Robust Tests of Equality of Means

	<i>Statistic^a</i>	<i>df1</i>	<i>df2</i>	<i>Sig.</i>
<i>Welch</i>	11.876	2	41.570	.000
<i>Brown-Forsythe</i>	7.955	2	48.155	.001

a. Asymptotically F distributed.

Figure E. 2 Mean Plot of Field Permeability Coefficients for Different Field Compactors

Appendix F Laboratory Permeability of Different Roller Compacted Cores

Table F. 1 Lab. Permeability of Cores Compacted by Different Compaction Method

<i>Roller</i>	<i>Lab. Permeability (cm/secs)</i>	<i>Roller</i>	<i>Lab. Permeability (cm/secs)</i>	<i>Roller</i>	<i>Lab. Permeability (cm/secs)</i>	<i>Roller</i>	<i>Lab. Permeability (cm/secs)</i>
<i>SGC</i>	<i>0.00E+00</i>	<i>AMIR</i>	<i>2.87E-03</i>	<i>AMIR</i>	<i>3.18E-03</i>	<i>Oscillatory</i>	<i>7.56E-04</i>
<i>SGC</i>	<i>8.10E-06</i>	<i>AMIR</i>	<i>2.83E-03</i>	<i>AMIR</i>	<i>3.02E-03</i>	<i>Oscillatory</i>	<i>7.48E-04</i>
<i>SGC</i>	<i>2.05E-04</i>	<i>AMIR</i>	<i>4.51E-06</i>	<i>AMIR</i>	<i>7.57E-04</i>	<i>Oscillatory</i>	<i>7.34E-04</i>
<i>SGC</i>	<i>1.87E-04</i>	<i>AMIR</i>	<i>0.00E+00</i>	<i>AMIR</i>	<i>7.22E-04</i>	<i>Oscillatory</i>	<i>7.46E-04</i>
<i>SGC</i>	<i>4.51E-04</i>	<i>AMIR</i>	<i>3.80E-04</i>	<i>Vibratory</i>	<i>1.05E-04</i>	<i>Oscillatory</i>	<i>2.20E-03</i>
<i>SGC</i>	<i>4.50E-04</i>	<i>AMIR</i>	<i>3.05E-04</i>	<i>Vibratory</i>	<i>7.98E-05</i>	<i>Oscillatory</i>	<i>2.20E-03</i>
<i>SGC</i>	<i>2.35E-04</i>	<i>AMIR</i>	<i>2.80E-04</i>	<i>Vibratory</i>	<i>1.15E-03</i>	<i>Oscillatory</i>	<i>1.59E-03</i>
<i>SGC</i>	<i>2.02E-04</i>	<i>AMIR</i>	<i>2.82E-04</i>	<i>Vibratory</i>	<i>1.10E-03</i>	<i>Oscillatory</i>	<i>1.26E-03</i>
<i>SGC</i>	<i>3.71E-04</i>	<i>AMIR</i>	<i>2.72E-04</i>	<i>Vibratory</i>	<i>1.01E-03</i>	<i>Oscillatory</i>	<i>1.00E-03</i>
<i>SGC</i>	<i>3.07E-04</i>	<i>AMIR</i>	<i>8.33E-05</i>	<i>Vibratory</i>	<i>8.91E-04</i>	<i>Oscillatory</i>	<i>8.44E-04</i>
<i>SGC</i>	<i>2.77E-04</i>	<i>AMIR</i>	<i>7.97E-05</i>	<i>Vibratory</i>	<i>2.69E-04</i>	<i>Oscillatory</i>	<i>1.98E-03</i>
<i>SGC</i>	<i>7.98E-04</i>	<i>AMIR</i>	<i>6.36E-05</i>	<i>Vibratory</i>	<i>2.58E-04</i>	<i>Oscillatory</i>	<i>1.90E-03</i>
<i>SGC</i>	<i>7.86E-04</i>	<i>AMIR</i>	<i>6.31E-05</i>	<i>Vibratory</i>	<i>2.46E-04</i>	<i>Oscillatory</i>	<i>1.73E-03</i>
<i>SGC</i>	<i>7.66E-04</i>	<i>AMIR</i>	<i>3.81E-05</i>	<i>Vibratory</i>	<i>2.46E-04</i>	<i>Oscillatory</i>	<i>1.49E-03</i>
<i>SGC</i>	<i>1.03E-03</i>	<i>AMIR</i>	<i>1.66E-03</i>	<i>Vibratory</i>	<i>3.07E-03</i>	<i>Oscillatory</i>	<i>3.23E-03</i>
<i>SGC</i>	<i>8.64E-04</i>	<i>AMIR</i>	<i>1.60E-03</i>	<i>Vibratory</i>	<i>2.78E-03</i>	<i>Oscillatory</i>	<i>3.11E-03</i>
<i>SGC</i>	<i>7.28E-04</i>	<i>AMIR</i>	<i>1.58E-03</i>	<i>Vibratory</i>	<i>2.14E-03</i>	<i>Oscillatory</i>	<i>3.11E-03</i>
<i>SGC</i>	<i>2.55E-03</i>	<i>AMIR</i>	<i>1.51E-03</i>	<i>Vibratory</i>	<i>1.72E-03</i>	<i>Oscillatory</i>	<i>3.01E-03</i>
<i>SGC</i>	<i>2.38E-03</i>	<i>AMIR</i>	<i>1.18E-03</i>	<i>Vibratory</i>	<i>1.57E-03</i>	<i>Oscillatory</i>	<i>1.81E-03</i>
<i>SGC</i>	<i>2.38E-03</i>	<i>AMIR</i>	<i>1.14E-03</i>	<i>Vibratory</i>	<i>3.50E-03</i>	<i>Oscillatory</i>	<i>1.63E-03</i>
<i>SGC</i>	<i>3.03E-04</i>	<i>AMIR</i>	<i>1.08E-03</i>	<i>Vibratory</i>	<i>3.35E-03</i>	<i>Oscillatory</i>	<i>1.36E-03</i>

<i>SGC</i>	<i>3.00E-04</i>	<i>AMIR</i>	<i>1.15E-03</i>	<i>Vibratory</i>	<i>3.37E-03</i>	<i>Oscillatory</i>	<i>1.17E-03</i>
<i>SGC</i>	<i>3.01E-04</i>	<i>AMIR</i>	<i>1.95E-03</i>	<i>Vibratory</i>	<i>3.29E-03</i>	<i>Oscillatory</i>	<i>1.11E-03</i>
<i>SGC</i>	<i>3.33E-04</i>	<i>AMIR</i>	<i>1.82E-03</i>	<i>Vibratory</i>	<i>3.84E-03</i>	<i>Oscillatory</i>	<i>1.08E-03</i>
<i>SGC</i>	<i>2.72E-04</i>	<i>AMIR</i>	<i>1.67E-03</i>	<i>Vibratory</i>	<i>3.58E-03</i>	<i>Oscillatory</i>	<i>1.04E-03</i>
<i>SGC</i>	<i>2.02E-03</i>	<i>AMIR</i>	<i>1.54E-03</i>	<i>Vibratory</i>	<i>3.44E-03</i>	<i>Oscillatory</i>	<i>1.04E-03</i>
<i>SGC</i>	<i>1.93E-03</i>	<i>AMIR</i>	<i>8.03E-04</i>	<i>Vibratory</i>	<i>3.29E-03</i>	<i>Oscillatory</i>	<i>2.80E-03</i>
<i>SGC</i>	<i>1.71E-03</i>	<i>AMIR</i>	<i>6.91E-04</i>	<i>Vibratory</i>	<i>5.32E-03</i>	<i>Oscillatory</i>	<i>2.71E-03</i>
<i>SGC</i>	<i>6.18E-04</i>	<i>AMIR</i>	<i>6.57E-04</i>	<i>Vibratory</i>	<i>5.38E-03</i>	<i>Oscillatory</i>	<i>2.63E-03</i>
<i>AMIR</i>	<i>3.05E-03</i>	<i>AMIR</i>	<i>3.18E-03</i>	<i>Vibratory</i>	<i>5.40E-03</i>	<i>Oscillatory</i>	<i>2.49E-03</i>
<i>AMIR</i>	<i>2.92E-03</i>	<i>AMIR</i>	<i>3.18E-03</i>	<i>Vibratory</i>	<i>5.49E-03</i>		

Table F. 2 Descriptive Statistics of All Lab. Permeability Values

	<i>Descriptives</i>		
	<i>N</i>	<i>Mean</i>	<i>Std. Deviation</i>
<i>AMIR</i>	37	0.0013	0.0011
<i>Oscillatory</i>	30	0.0018	0.0008
<i>SGC</i>	29	0.0008	0.0008
<i>Vibratory</i>	27	0.0024	0.0018
<i>Total</i>	123	0.0015	0.0013

Table F. 3 Levene's Test of Homogeneity of Variances of Lab. Permeability Values

	<i>Levene</i>	<i>df1</i>	<i>df2</i>	<i>Sig.</i>
	<i>Statistic</i>			
<i>Based on Mean</i>	14.622	3	119	.000
<i>Based on Median</i>	11.919	3	119	.000
<i>Based on Median and</i>	11.919	3	93.603	.000
<i>with adjusted df</i>				
<i>Based on trimmed mean</i>	14.628	3	119	.000

Table F. 4 Robust Tests of Equality of Means

	<i>Statistic^a</i>	<i>df1</i>	<i>df2</i>	<i>Sig.</i>
<i>Welch</i>	10.758	3	62.837	.000
<i>Brown-Forsythe</i>	9.801	3	66.786	.000

a. Asymptotically F distributed.

Figure F. 1 Mean Plot of Lab. Permeability Coefficients for Different Compacted Cores