Technical and Economic Development of Efficient Asphalt Multi-Integrated Compaction Technology

by

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Abstract

The search to perform asphalt compaction process utilizing a single independent roller started over a century ago. Unfortunately, instead of correcting imperfections in the roller's design and operation, the world has performed field compaction of asphalt in three distinct stages with three different rollers. Despite the utilization of three rollers to compact new asphalt layers, premature failure of asphalt mat has been found in carefully conducted independent audits of government appointed agencies.

While most of the research work in the asphalt field pointed to the asphalt mix and environmental factors that cause early deterioration of newly constructed asphalt roads, a new roller termed Asphalt Multi Integrated Roller (AMIR) offered better compaction method which corrected the imperfections of the current compaction technologies. Though, the AMIR compaction technology was invented in the 1980s, it has not been widely utilized by the highway construction industry. Independent researchers have established that failure of asphalt mat is due to entry of air and water into the mat. Up to the present time, most road authorities around the world do not have a standard testing method or a minimum value for permeability in compacted asphalt mat to enhance acceptance criteria.

This research examined the compacted asphalt mat pavement properties and performance of several field trials using three stage and single stage compaction methods. The trial mats compacted on binder, granular and concrete bridge deck bases. The impartial investigation was conducted over six years and recommends that the effective economical and sustainable way to improve long term performance of asphalt pavements is to replace the current three stage field compaction with the AMIR.

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Chapter 1 : Introduction

1.1 Background

In order to understand the term "asphalt pavement compaction", it is necessary to determine what is meant by asphalt pavement and compaction. The following definitions were simplified using the class notes (Abd El Halim A. O., 2012), reference book (Mallick & El-Korchi, 2013) and website (Pavement Interactive, 2018). Asphalt pavement is composed of a combination of coarse and fine aggregates along with mineral fillers held together by asphalt cement. Compaction is the process of reducing the amount of air in the asphalt mixture and repositioning aggregate particles closer together to create a denser and more effective mixture. Reducing the amount of air increases the strength of an asphalt mix and the density (i.e. mass by volume). Field cores obtained from asphalt pavement roadway and its density examination in the laboratory provides the field compaction quality information.

Most of the road authorities in North America and many parts of the world depend only on measurements of density of asphalt cores to assess the quality of materials received (Ministry of Transportation Ontario, 2015). The asphalt pavement structural design primarily assumes that an asphalt layer is impermeable (Williams, 2009). Minimizing moisture infiltration from top layers in order to maintain adequate support in the underlying materials forms the base for the mix design approach. Lower in place density caused by poor compaction allows air and water to enter asphalt layer and leads to asphalt mat failure (Roberts et al.,1991; Brown et al.,2004). Unfortunately, most road authorities in Canada and elsewhere do not possess a standard test or minimum value for permeability that is the amount of water that needs to penetrate through the compacted asphalt layer (Ministry of Transportation Ontario, 2010).

During the construction phase, two basic pieces of equipment were available for compaction: a

paver screed and a roller. Most of the compaction density in an asphalt mix (75 to 85 percent) is acquired by passing the mix through a paver screed (Pavement interactive, 2018). The remaining percent of compaction density is achieved using current field compaction method. These typically involve three stages (breakdown, intermediate and finish) and three different rollers (vibratory or oscillating, pneumatic tire and static smooth). This current compaction method (CCM) has been practiced in Ontario, Canada since 1970 (Leckie, 1973).

The three stages in CCM are required because of hairline cracks caused during the breakdown stage of the compaction due to the use of the vibratory or oscillating steel drum roller. These cracks result in the need for intermediate stage using a pneumatic tire roller to seal the crack. While the cracks remain, the tire marks left during this stage required a smooth steel roller into the rolling train to produce a finish mat free from roller marks (Fromm, 1964). It is important to note that construction cracks have been recognized for long time but were not consider affecting the long-term performance of the paved roads as will be discussed later.

The expected design service life of Ontario asphalt pavement is 15 to 20 years (Auditor General, 2016). Decades of research as well as the 2016 Ontario Auditor General Report, indicate that the design objectives of asphalt pavement are rarely met, despite significant improvements in asphalt mix quality, testing methods, contract specifications and workmanship. The longitudinal joint of an asphalt mat is commonly where repairs are needed well before the end of the expected design service life caused by receiving less compaction (Pavement Interactive, 2018).

The CCM requires expensive alternate methods such as echelon paving, joint heaters for longitudinal joints to receive compaction similar to rest of the asphalt mat (Pavement Interactive, 2018; Ministry of Transportation Ontario, 2008). Lack of funding prevents most road authorities from specifying quality longitudinal joint construction methods as their standard specifications. Moreover, to prevent damage to bridge structure from CCM roller vibration during asphalt

overlay on bridge decks, road authorities specify vibration free two-stage compaction using tire and smooth rollers (Ministry of Transportation Ontario, 2015).

Advance in contract specifications, including end-result and performance-based (Ministry of Transportation Ontario, 2015), improvement in mix design like Superpave, implementation of certification (CCIL, 2018) and training methods (Toromont Caterpillar, 2018) for technicians and operators have improved pavement construction workmanship. However, the potential improvement from high-quality mix and improved workmanship were never achieved, as the results were less than optimal. These conclusions necessitate for better understanding of asphalt mat compaction, the relationship between the types of compaction technologies, standard permeability testing and acceptance criteria.

Canadian inventor and Carleton University Professor, A.O. Abd El Halim invented the Asphalt Multi Integrated Roller (AMIR) compaction technology in the 1980's. Although the AMIR roller prototype prevented check or construction cracks, enhanced joint, and edge compaction (Abd El Halim 1982-2008), the technique was not widely used. One reason for this was insufficient field data due to poor funding. Highway construction projects are typically funded by taxpayers, and premature asphalt pavement failure can decrease the value for the taxpayer dollars. Adopting the most effective, economical and sustainable compaction method and adding new field-testing procedures will increase the overall quality of asphalt surface. Two key reasons for the premature asphalt pavement failure are the imperfections in the CCM and failure to improve compacted asphalt mat quality acceptance standards. Therefore, improving the compaction method is essential, as is adopting new or additional quality standards to reduce expenditure for resurfacing asphalt pavement due to premature failure. Most current research is focused on improving the asphalt mix design, laboratory testing protocols and pavement management systems, with minimal effort applied to investigating compaction technology and field permeability criteria.

1.2 Problem definition

Compaction process is recognized as one of the most important factors affecting performance of asphalt pavement (Pavement interactive, 2018). The need to perform research with on-site compaction equipment came from observing construction cracks in the field. The load carrying capacity of a loose asphalt mix is improved in the laboratory by using a single compaction equipment know as gyratory compactor. The required size and strength of asphalt briquettes in the laboratory is achieved without applying vibration or changing the compaction equipment.

Although, compaction in the field can be done effectively using a single roller, in Canada and other countries, the field compaction is performed in three stages with three different rollers. In Ontario, asphalt pavement compaction for bridge deck asphalt overlays requires two independent rollers for two separate stages in compaction as part of work project contract requirements, as per section seven subsection no. 10 of OPSS No.313 (Ministry of Transportation Ontario, 2015). Absence of innovative design improvements in the CCM over the last 50 years has increased the cost of publicly funded highway construction projects, in terms of equipment, workers and time. The purpose of compaction is to ensure that pavement is waterproof by incorporating correct air voids and shear strength (Williams, 2009). Most road authorities like MTO, control asphalt mat permeability through compaction by controlling the air voids for different size aggregates, as per OPSS No 313 (Ministry of Transportation Ontario, 2015). Though, the pavement is considered as waterproof, there is no standard minimum requirement or test method to determine if an asphalt mat in the field has achieved the required permeability.

The literature review for this study found only one alternative compaction method using a single standalone roller in Ontario, Canada the “Asphalt Multi Integrated Roller” (AMIR) prototype. Thus, the AMIR compaction method is proposed and applied in this research to determine if

CCM compaction problems are communal. Despite, the AMIR compaction technology was invented in the 1980's, it has not been widely utilized by the highway construction industry due to lack of technical and economic information.

This study will provide data and information that will allow the highway construction industry to recognize the technical and economic benefits of the AMIR compaction method by addressing the following questions:

1) How does the quality of AMIR compacted pavement compare to that of pavement finished using CCM?
2) Are standard test and minimum requirements for permeability needed?
3) What are the optimal compaction specifications for the AMIR roller i.e. rolling temperature, number of passes, lift thickness?
4) What is the likelihood of the compaction method influencing pavement performance and permeability?
5) What are the economic benefits of using the AMIR roller?
6) How the AMIR compacted asphalt mat is performing under traffic operation after three to six years in service?

Compaction and quality acceptance practices are two issues required consideration of their effect in long-term performance of asphalt pavements. Reducing number of equipment which do not improve the quality of finished pavement in the compaction process and adopting new quality control testing such as permeability will increase the pavement quality, construction zone safety and reduce laying cost and carbon emission. Moreover, a slight increase in pavement performance will save taxpayer's dollars in millions (Kerr Staff, 2018),

1.3 Scope and objectives

The scope of this thesis is to provide sufficient data and information to enable the highway construction industry to realize the technical and economic benefits of the AMIR compaction method. The following objectives are addressed by comparing CCM with the AMIR. First, the quality is assessed by comparing properties of compacted asphalt pavements. Second, the optimal compaction parameters of the AMIR are discussed. Third, a mathematical model is suggested to determine the compaction methods influence on pavement performance and permeability. Fourth, the economic impact of the two compaction methods is evaluated in terms of equipment, manpower and time frames. Finally, a maximum of six years is set as the term for performance review of asphalt mats compacted by both methods. This is done by monitoring the asphalt mat status under traffic and climatic conditions at a minimum of three independent sites. Although the prime focus of the study is Ontario provincial highways, the outcomes could be applied elsewhere.

1.4 Research plan

The experimental design plan shown in Figure 1-1 clearly identifies the research questions and eliminates systematic and personal biases. The plan is divided into three phases: Phase I: Field testing, Phase II: Laboratory testing, and Phase III: Analysis. The results and observations of Phases I and II will be used for analysis of quality, cost and performance in Phase III. The following requirements of the research plan were followed:

1) Trial sections of asphalt pavement overlay on granular and concrete bridge deck bases, were laid following the MTO standard specification OPSS No.313 (Ministry of Transportation Ontario, 2015) with side-by-side compaction of asphalt trial section using the CCM and the AMIR methods. This is to provide required information about the

compacted pavement quality and to replicate the trials consistently at other locations without any bias.

2) Randomized sampling techniques by following the MTO 2006 field guide on the acceptance of hot mix and water proofing for field core collection points to avoid personal bias.
3) Field permeability testing using NCAT permeameter. Field cores were extracted immediately after field permeability testing before allowing public traffic on paved asphalt surface to eliminate the effect of compaction through vehicle.
4) Density testing of the field cores following MTO laboratory standard LS 262 (Ministry of Transportation Ontario, 2010), to replicate the compacted material property consistently.
5) Analysis of field data for mathematical model and observation of construction procedure and equipment to estimate cost and benefit.
6) Performance assessment of the side-by-side compacted field trial area for a maximum of six years to collect maximum behavioral information regarding the compacted mat. The expected design service life of Ontario asphalt pavement is 15 years (Auditor General, 2016) and transportation agency like the MTO acceptance of general warranty for workmanship and quality is one year (general condition, section 7, subsection 8.02 in OPSS No.100 (Ministry of Transportation Ontario, 2015)). The performance review period of a maximum of six years will provide an outcome that is 6 times more than the current requirement of the general warranty provided by the contractors to the road authorities and will disclose surface condition at 40% of the asphalt design service life.

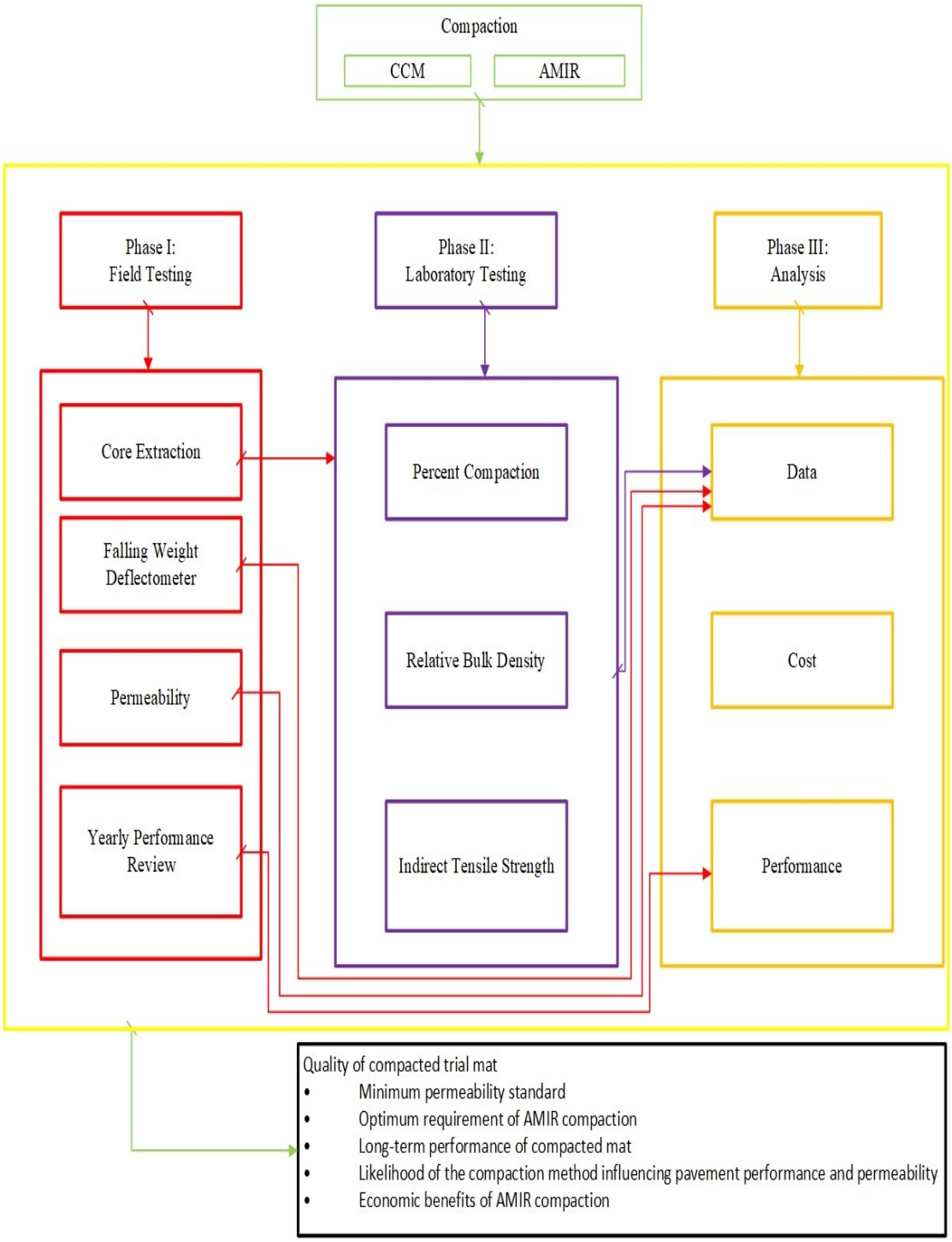


Figure 1-1 Experimental plan

1.5 Expected contribution to literature

The unique contributions of this thesis are seven-fold. First, the research study conducted field trials operating the AMIR roller side by side with the CCM rolling train for the first time on

various provincial road sections, while carefully following provincial standard specifications for placement, compaction and acceptance of hot mix OPSS No.313. Second, the in-house trials provided sufficient information to achieve optimum values of compaction including temperature, thickness and number of passes required by the AMIR compaction method; this was not determined in previous studies of the AMIR in Canada. Third, for the first time the AMIR prototype was used for bridge deck asphalt overlay compaction to understand compaction quality. Fourth, for the first time a minimum of three to six years of performance monitoring revealed the comprehensive pavement performance of the AMIR method. Fifth, field permeability is not a standard test, for the first time through this research, MTO adapted field permeability into their contracts to understand testing procedure and standardization requirements. Sixth, employing a mathematical model(s) will help identify the fundamental relationships of compaction method with long-term performance and permeability. The significance of the developed model can be realized when reviewing performance models developed in the literature. Seventh, cost estimates, also for the first time, will help to identify whether the AMIR compaction is more economical than CCM in terms of equipment, manpower, time and maintenance.

Chapter 2 : Literature review

2.1 Asphalt pavement structures

A pavement structure is the portion of the road designed to be a running surface and support for vehicular traffic (Mannering et al., 2013). The following definitions were simplified using the class notes (Abd El Halim A. O., 2012), Asphalt paving is the technique used to lay an asphalt mixture as the top layer of the pavement structure. The Asphalt mixture of a pavement is an engineered composite material made by binding aggregate materials together with glue. The glue fraction (asphalt) contributes to the predictable and reproducible characteristics. Aggregate contributes the bulk and the economy. The asphalt pavement structure on a granular base is depicted by the construction sequence shown in Figure 2.1.

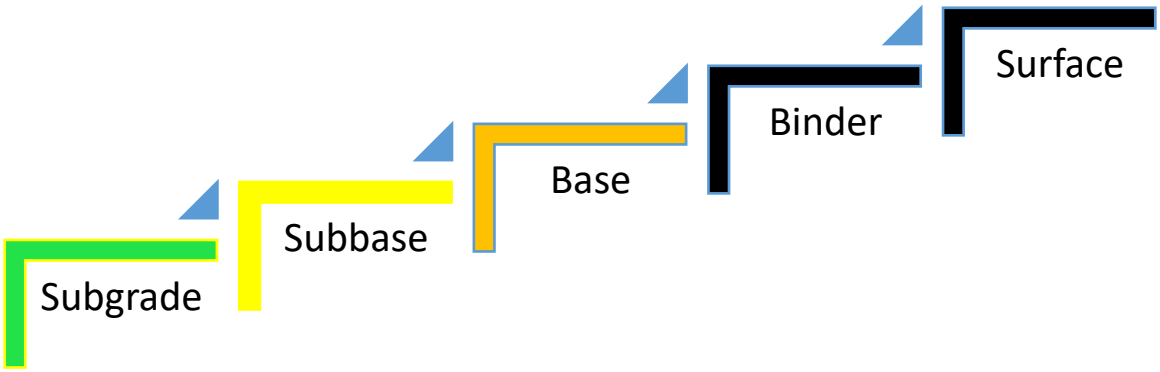


Figure 2-1 Schematic construction sequence of the asphalt pavement structure

1) Subgrade

The subgrade is where new layers are constructed to form the asphalt pavement structure. It is typically prepared by removing or placing native soil material and manipulating it to serve as the foundation for the pavement structure.

2) Granular subbase course

Above the subgrade is the subbase course. The primary function is to provide structural support, minimize frost damage and to provide a working platform for construction of the pavement.

3) Base course

The base is directly above subbase course and is typically constructed with durable, high quality aggregates. The base course functions as a structural layer, which transmits and distributes the traffic loads from the asphalt layer to lower layers.

4) Binder course

The binder course above the base and is generally constructed with asphalt binder and aggregates of lower quality than those in the surface course. The role of the binder course is to improve the strength of the pavement structure and to distribute the load to the base.

5) Surface course

The surface course is the top layer and is in contact with traffic operations. It contains high quality aggregates and contributes to friction, smoothness, noise control, drainage, rut and shoving resistance.

2.2 The importance of compaction

Compaction is the least expensive way to extend the service life of asphalt pavement (Brown et al., 2017). The importance of the compaction according to compacted surface properties is discussed below:

1) Increased stiffness and strength

Reducing the air void content of the loose mix increases the stiffness and strength of pavement, as indicated by Kennedy et al., (1984). Research work by Kassem et.al., (2012) demonstrated asphalt samples with less percent air voids performed better in wet and dry conditions, caused less rutting in the Hamburg wheel- tracker, achieved higher strength in the indirect tensile test. Bijleveld et. al., (2012) of Netherlands demonstrated through literature review, laboratory-

experiments and field data-collection that compaction temperature influence density and mix properties of an asphalt mixture. His field trials were conducted in asphalt paving research and innovation network created by the University of Twente and 11 Dutch contractors. Bijleveld et. al. suggested field and laboratory quality control process for asphalt mix compaction should include compaction temperature to avoid variability in results and quality. Compaction effort on an asphalt mat in the field depends on the asphalt binder grade and amount, aggregate angularity, size and hardness and layer thickness (Ministry of Transportation, 2013).

2) Increased fatigue life

Several researchers have highlighted the relationship between reduced air voids and increased fatigue life Epps et al., (1969), Seeds et al., (2002) and Fisher et al., (2010) concluded a reduction in loose mix air voids from 11.5% to 4% could double pavement fatigue life. Effect of in-placed air voids on life cycle cost for a design life period of 20 years was analyzed by Tran et al., (2016). The analysis reported by reducing the minimum required in-place air voids by 1% from 8% to 7% in a $1,000,000 paving project could save 8.8% in a net present value cost.

3) Reduced moisture damage

Many researchers have reported that compaction is a major construction variable than can reduce the stripping potential of an asphalt mixture. It is accepted from various studies that poorly compacted asphalt has increased air voids, and that they tend to be interconnected (Zube, 1962; Cooley et al., 2002; Vardanega P. J., 2014). The concept of "pessimum" (opposite of optimum) air voids content that ranges from greater than 5% and less than 15% proposed by SHRP A-003A researchers relates to stripping potential in an asphalt mixture. The stripping potential is increased early in the life of an asphalt mat as most of them are constructed in pessimum range that allow water to enter thru interconnection of some air voids and cause the water to trap in the mixture (Terrel et al., 1989). The relationship between permeability and air voids is quite

important and can be altered significantly by changes in parameters such as nominal maximum aggregate size, mix gradation, binder content and lift thickness change (Williams, 2009; Vardanega P. J., 2014).

4) Reduced aging acceleration, increased durability, and increased service life

McLeod (1956) and Wang et al.,(2015) stated that better pavement performance can be achieved by reducing the rate of asphalt binder hardening by compacting a well-designed paving mixture to low air voids. Based on New Jersey department of transportation data base of 55 pavement sections, it was concluded by Wang et al., (2015) that service life (time from initial construction until the next rehabilitation) of an asphalt pavement could increase by 10% by a decrease of 1% in in-place air voids.

5) Reduced construction cracks with increased joint and unsupported edge compaction

It is acknowledged that asphalt pavement structural design primarily assumes an asphalt layer is impermeable (Ministry of Transportation, 2013). The reason is to control moisture infiltration from top layers that will maintain adequate support in the underlying materials. Several researches around the world have provided early evidence of top down cracks thru field cores Dauzats et al., (1982) of France, Pronk et al., (1982) of Netherlands, Hugo et al., and Strauss et al., (1984) of South Africa, Nunn et al., (1997) and Phillips (1999) of United Kingdom. Nesnas et al., (2004) of United Kingdom kept trial section without allowing traffic for over 12 years since its construction to provide evidence that cracking pattern similar to the section with traffic could occur in the absence of traffic. Ferne cited all the above researchers work to suggest that surface cracks are caused and progressed by environmental effects such as temperature cycles (Ferne, 2005)

Numerous studies by Abd El Halim et al., (1985,2006,2016) identified that deficiencies in the roller design induce construction cracks at the top of asphalt surface which propagates horizontal,

transverse and downwards by interconnection of constructions cracks. The progression of the cracks varies depending upon environmental factors, timing and effectiveness of maintenance treatments and (Ferne, 2005). There are many ways for moisture to enter in the asphalt pavement. One such way for moisture entry identified by Abd El Halim et al., (1985) is during compaction process in the construction stage. Poor compaction or method choice could cause construction cracks, high air void content and loose surface texture. Moisture and air may enter through poorly compacted asphalt mixture under favorable condition is capable of break or strip the bond (known as stripping) between asphalt binder and aggregate. The loss of bond through stripping often accelerates pavement deterioration. Asphalt surface that allows water (permeable surface) increases the potential of air, oxygen in the air react with asphalt surface, reaction known as oxidation. The oxidation over a period could cause the asphalt pavement to fail by making the asphalt to brittle, reducing load carrying capacity, resulting in fatigue, and cracking (Abd El Halim et al., 2006). Pavement fracture under repeated changeable loading of vehicles is known as fatigue in the asphalt pavement. Poor compaction may result in low load resistance capacity (stiffness) of the asphalt mat that leads to create fatigue cracks at the top pavement. The presence of construction cracks on the pavement surface can advance micro cracks known as thermal cracks developed by the temperature drop in weather. Repeated cycle of fluctuating temperature quickens the micro cracks to extend full depth of the asphalt layer causing the pavement to fail by thermal cracking (Abd El Halim et al., 2013). Reflective cracks such as fatigue and thermal are created during compaction at the surface extends to the bottom of the mat by joining to the existing cracks which can utlimately leads to pothole.(Abd El Halim et al., 2016).

Several factors (like design, aggregate selection, etc.) are involved to prevent premature failure of the asphalt pavement. One such factor is providing crack free tighter textured finished asphalt surface by rectifying current compaction method (CCM) defects. The crack free and tighter

texture of asphalt surface can act as a first line of defense to prevent water and air entry and ultimately extend the service life of the asphalt pavement. Numerous studies suggest that eliminating construction induced cracks and improving compaction at centerline joints and unsupported edges results in tighter surface texture, reduced permeability, improved construction joint and unsupported edge performance (Abd El Halim et al., 2013, 2016).

To summarize, reducing the volume of air in the loose mix through compaction increases the density (unit weight) of the mix. A well laid and compacted asphalt surface will have evenly distributed density, tighter surface texture, and a decrease in permeability of the asphalt mixture. A tighter surface texture protects the underlying layers in the overall structure, and ultimately increases the service life of the pavement structure.

2.3 Compaction equipment evolution

To fully understand the three-stage current compaction method (CCM), it is important to be aware of the evolution of compaction equipment in the North American highway construction industry.

2.3.1 Static single drum roller

Thomas Aveling invented the first steamroller in 1865. The initial trial was conducted on December 15, 1866 in Hyde Park, London, England and was reported in the Illustrated London News. Since the trial demonstrated that using mechanical compaction could produce an excellent ride quality of the finished surface at a decreased cost, the use of horse drawn rollers for road construction eventually ended. The first single cylinder, eight-horsepower gasoline driven roller was released in 1905. Further development produced the first diesel powered single drum roller in 1927. The high performance of diesel and gasoline driven engines eventually resulted in the disappearance of the steamroller for highway construction (Charles, 1960). It is important to mention that the developed drum rollers were not based on in-depth analytical studies that

investigate the interaction between the stiff steel drums and soft flat asphalt mixes during compaction.

2.3.2 Static tandem roller

According to a 1940 pamphlet published by the Buffalo-Springfield Roller Company, the first steam driven roller in the United State was designed and built by Andrew Lindelof in 1898. Initial problems such as rocking motion due to the heavy slow piston, waves in the finished rolled surface and operational difficulties with drive gear were solved in subsequent attempts. In 1929, the company produced a six-cylinder gasoline powered tandem roller with a superior cooling system. The difficulties of the improved tandem roller included the roller following the contour of the road, causing variations in ride quality (Charles, 1960).

2.3.3 Static inter roller

The idea of using of an extra roller, or a third axle, without synchronized steering was introduced by Austin-Western in 1934 and it was called the Roll-A-Plane Roller. The rationale of the three-wheel, tricycle-type roller was to have the roller wheels on separate axles on a straight plane would transfer the weight and pressure to the roller on the highest point of the surface. However, the amount of pressure transferred was dependent on vertical height of the roller, which is related to roller diameter. Thus, the smaller diameter of the rollers resulted in increased horizontal pressure on the asphalt mat, causing it to fail.

In 1935, Buffalo-Springfield introduced an inter-roll or third axle with larger diameter rollers that could be raised and lowered, and double synchronized steering to overcome the design problems encountered in1934. This roller was the most popular for asphalt pavement compaction until the introduction of the pneumatic tire roller (Charles, 1960).

2.3.4 Pneumatic tire roller

According to H.J. Fromm, a representative of the MTO, a conventional rolling train in Ontario during the 1950s typically had a 10 to 12-ton steel drum static roller for breakdown, an eight-ton steel drum static roller for intermediate and an eight-ton steel drum static roller for finishing. MTO field verification found that the air void target was not achieved constantly and that there was considerable variation in compaction in completed work projects using three static steel drum rollers. The introduction of the pneumatic tired roller in 1937, with its improved compaction results, persuaded MTO authorities to substitute one of the steel rollers with a pneumatic tire roller in 1961. Table 2-1 below shows the roller sequence order suggested by Fromm (1964).

Table 2-1 Ontario provincial highway roller sequence in the 50's

Roller Sequence	Roller Category	Weight in Ton	Roller Type	Number of Passes
1	Break down	12	Static tandem roller	5-7
2	Intermediate	30	Pneumatic	13
3	Finishing	8	Static tandem roller	3

H.J. Fromm conducted a study by keeping number of passes constant for all three types of rollers, in seven different rolling sequences on six different contracts. The intent was to better understand the effect of changing roller positions in the rolling sequence during the compaction stage. The goal was to produce consistent high compaction values and good ride quality of the finished pavement. He found that replacing the intermediate roller with a pneumatic roller removed construction cracks created by the breakdown steel roller and using the static steel roller for finishing removed the tire marks of the intermediate tire roller. This combination of static, pneumatic and static rollers produced the highest degree of compaction and good ride quality.

2.3.5 Vibratory roller

In search of standalone rolling equipment, MTO officials conducted vibratory roller field studies in 1970 and 1972. David Leckie a representative of the MTO, performed studies on 12 work projects, each with a different asphalt mix. He used mini road logger equipment to compare the standalone vibratory roller compaction quality to a rolling train with a 12-ton static roller (break down), a 9-ton or 30-ton pneumatic tire roller (intermediate) and an eight-ton tandem roller (finish). He also changed the rolling sequences by introducing a vibratory roller as breakdown, a pneumatic tire roller as intermediate and 8-ton tandem roller as the finish roller in order to determine the capability of vibratory roller in the rolling train for asphalt pavement compaction. Leckie determined that the vibratory roller is a good addition to the asphalt compaction rolling train, but it cannot be used as a standalone roller as it causes hairline construction cracks, surface rippling and poor joints. However, he found that using the rolling sequence of a vibratory roller as breakdown, a pneumatic roller as intermediate and a tandem roller for finishing in the rolling train produced adequate compaction and acceptable surface texture and joints. The sequence order shown in Table 2.1 was modified to accommodate the vibratory roller as the breakdown roller (Leckie, 1973). This sequence became popular and it is still practiced in Ontario and elsewhere in the current compaction method (CCM) format today, although there are variations in the weight of the equipment.

2.3.6 Oscillatory Roller

HAMM AG a subsidiary of Germany's Wirtgen Group Company invented oscillating rollers in 1983. The Oscillatory roller moves in a forward and backward rotary motion due to unconventional weightings and the motion guides the compaction to produce horizontal and

downward shear forces. The forces act dynamically without vibration allowing the circular steel drum to maintain contact with the asphalt mix (HAMM, 2017). Oscillation rollers cannot be used in all circumstances, as they require a conventional vibratory roller for breakdown, but eliminates finishing roller by operating as both intermediate and finishing rollers (Lombardo.S, 2018). An Oscillatory roller trial in Colorado, United States of America showed that the roller could compact longitudinal joints to the required target density (Wirtgen America Inc., 2004). However, this compaction method cannot produce adequate compacted surface without an additional roller, so the issues of construction cracks and inability to eliminate the additional roller persist in the HAMM compaction method.

At the time of this study, there were no adequate specifications from the road authorities for using oscillatory rollers in the province of Ontario. To examine the capabilities of this new compaction equipment, an Oscillatory roller was allowed to be tested side by side during an asphalt trial conducted as part of this thesis on November 2017 in Ottawa municipal Road (Didsbury Rd). The field trials were completed following the MTO standard specifications OPSS No.313. The trial confirmed that the Oscillatory roller cannot be implemented as a standalone roller. Photo 2.1 shows the comparison of compacted surfaces of the November 2017 trial. In fact, the used roller was followed by pneumatic rubber roller and still surface cracks were appeared after completing the compaction.

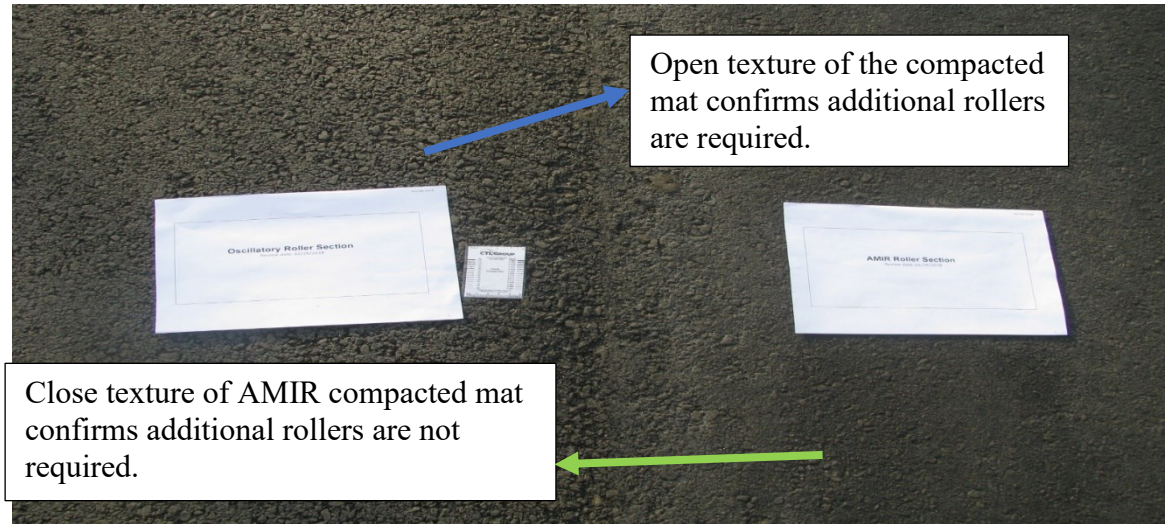


Photo 2-1 Comparison of compacted surface between HAMM and AMIR

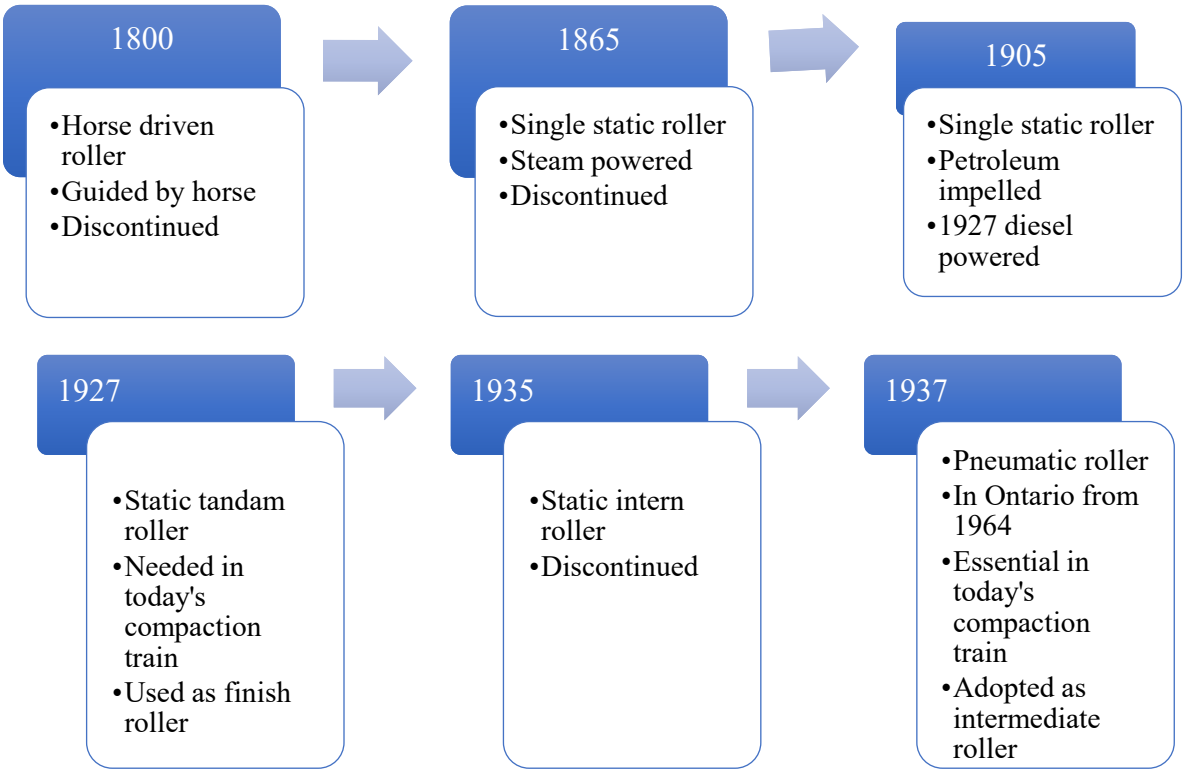
2.3.7 Intelligent compaction

Intelligent Compaction (IC) is a quality control method used during the construction of asphalt pavement. Adoption of IC in North America is as recent as 2007 (George et al., 2011) and has been slow due to unfamiliarity with operational aspects, and difficulties in verifying data in the field on completed pavement (Commuri et al., 2010). IC methods are based on the hypothesis that an IC system on a vibratory roller will help monitor vibrations of the roller in real time to estimate the stiffness. This allows for compaction shortfalls to be identified and corrected, while the mat is still workable (Beainy et al., 2014). Beainy et al., (2014) developed a model that they claimed could predict the compaction of hot mix asphalt in the field, but they did not include asphalt characteristics in their modelling. Not considering asphalt characteristics and its influence in IC system remains as an issue currently under study. At the time of this study, there was no adequate specification from the road authorities for IC in the province of Ontario.

To summarize, over the history of highway construction compaction equipment has always been considered essential. The highway construction industry and road authorities have been searching for a single stage compaction method that could satisfy their needs over 150 years, CCM roller deficiencies were known in Ontario since 1973 (Leckie, 1973) but design and

development has been lacking. These deficiencies eventually lead to the compaction method (breakdown, intermediate and finish) with three types of rollers (vibratory, pneumatic tire and smooth). This approach has been in practice for over 55 years, as it satisfies the road authority density requirements. During this study, the search for a single standalone roller from the highway construction industry is reduced drastically. The road and highway construction industry focus require to improve efficiency of three rollers in meeting client-targeted densification and to reduce the cost of the rollers through mass production.

Figure 2-2 depicts a synopsis of compaction equipment evolution.



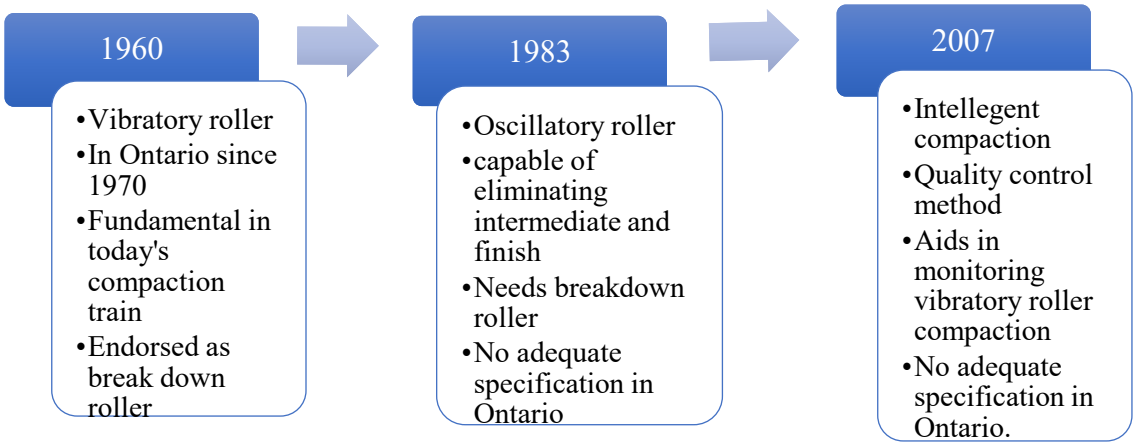


Figure 2-2 Compaction equipment evolution synopsis

2.4 Permeability

Interconnected air voids in the asphalt mix allow air, water, and water vapor to infiltrate into a pavement structure from the surface to base recognized as permeability (Asphalt Institute, 2018). McWilliams (1986) found the size and shape of the air spaces (voids) between the aggregate particles of hot-mix asphalt mixtures depends on the aggregate gradation, compaction effort, and the amount of the mineral filler or fine sand. The asphalt content, shape, and texture of the aggregate also influence void characteristics in a Hot Mix Asphalt (HMA) mixture. Roberts et al., (1991) stated that insufficient asphalt compaction can lead to increased water and air entry in the pavement. Water in the pavement structure leads to a variety of issues, including stripping and freeze/thaw damage. Air promotes the oxidation of asphalt cement, making the pavement more brittle and susceptible to longitudinal and fatigue cracking, as well as raveling. Huang et al., (1999), explained fundamentals of permeability in asphalt mixtures.

A study by Choubane et al.,(1998) using maximum density line which acts as a tool to compare gradation showed that gradations below the maximum density line are expected to be more permeable than mixes with gradations that pass above the maximum density line. Studies by

Mallick et al., (1999) and Liu et al., (2017) found that the nominal maximum aggregate size (Superpave method defined aggregate size), as influence with permeability. Moreover, larger nominal maximum aggregate size (NMAS) is more permeable, at a given air void content than mixes with smaller NMAS. Studies by Choubane et al., (1998) and Mallick et al., (1999) confirmed how gradation and nominal maximum aggregate sizes affect the size of air voids in compacted HMA.

Density that is too high or too low can lead to premature pavement failure (Killingsworth, 2004). Low in-place air voids are generally the result of a mix problem and high in-place voids are generally caused by inadequate compaction Brown et al., (2004). Brown et al., (2004) research work added that a lower percentage in-place voids can result in rutting and shoving, while higher percentages allow water and air to penetrate into a pavement, leading to an increased potential for water damage, oxidation, raveling, and cracking. Permeability increases with increase in-place voids (Vardanega et al., 2008; Vardanega P. J., 2014; Liu.H et al., 2017).

Christopher (2009) reported asphalt mix design method of most Superpave HMA mixes are coarsely graded than Marshall mixes. The coarse nature of Superpave mixes creates a greater potential for voids to be interconnected, exposing the pavement to the harmful effects of air and water. The coarser gradations of Superpave mixes have been successful at limiting distresses such as rutting but have resulted in other issues arising namely higher permeability than traditional mixes. Studies by Abd El Halim et al., (1999, 2006) suggest that infiltration in pavement structure takes place due to hairline cracks induced during compaction by the CCM.

The above-mentioned studies make it clear that some of the factors that influence the permeability of HMA are compaction, gradation, aggregate size and shape. Pavement compacted to a low density tends to have more and larger air voids which increases permeability. As road authority and the construction industry in Ontario have not addressed the issue of permeability,

the major steps leading to the understanding of whether compaction method affects the permeability and whether compaction method influence permeability and the long-term performance of compacted asphalt pavements are discussed and presented later in this thesis.

2.5 Deficiency of present compaction methods

There are number of deficiencies in CCM. They will be illustrated and elaborated on a sequential basis below:

2.5.1 Check or construction cracks

Asphalt pavement problems have been around for long time and numerous attempts were attempted with very little success. Research work of Abd El Halim A. O., (1985) showed that the major reason for asphalt pavement failure has to do with the interaction between the stiff steel rollers and the softer hot flat asphalt layer during compaction. Construction cracks or "check" are formed during the construction process. How construction cracks are formed is well explained in several papers of Abd El Halim et al., (1985,1991,2013). The CCM roller transfers stress in the form of intense pressure pulse for short duration through a circular shape (steel/tire) roller to a flat asphalt mat that causes the mat to change shape (deform) by receiving the shape of the roller drum. On the deformed asphalt mat around the roller drum, the roller movement applies horizontal forces and the deformed asphalt mat responds in the form of a high elastic stiffness. Instead of overcoming the stiffness of the asphalt mat by the current rollers, it increases the resilient modulus of the mat. Moreover; the use of steel as the roller material to compact a soft layer of asphalt mix on top of a dense base layer results in an unstable system due to relative rigidity. The above flaws cause the formation of hairline construction cracks as shown in Photo 2-2.

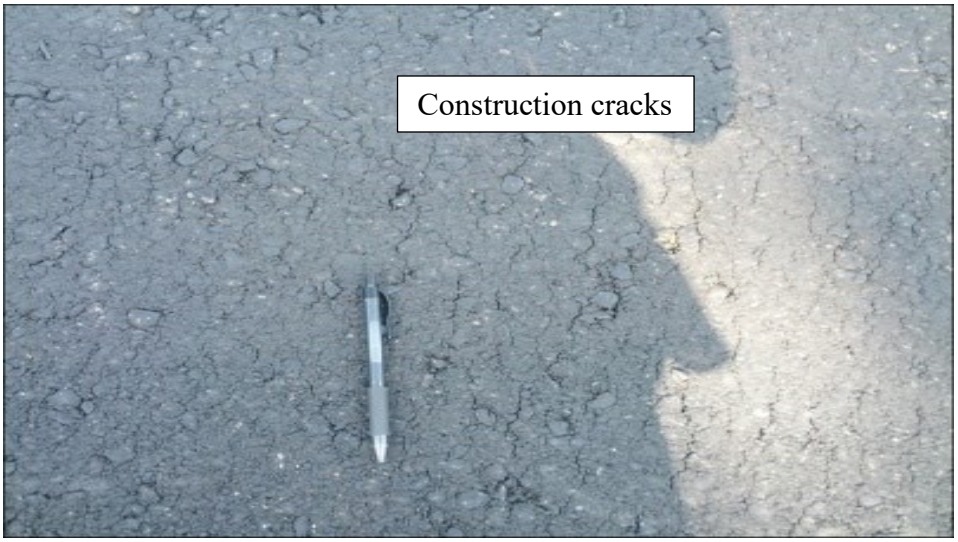


Photo 2-2 Construction cracks

The introduction of construction cracks at the top of asphalt mat has been noted and documented in Ontario, Canada for nearly 54 years ago (Fromm, 1964). Abd El Halim et al., (2006) suggest that the construction cracks at the top of asphalt may spur deficiencies such as stripping, fatigue and thermal cracking in the asphalt mat.

According to the highway construction industry and road authorities the main reasons for construction cracks are the combination of one or more of the following: poor asphalt mix; poor base stability; operator error; and poor choice of compaction temperature (Geller, 1982). The actual cause for construction cracks, i.e., steel drum roller has been recognized for more than half a century, disregarding this fact has led to other rollers such as pneumatic and vibratory rollers being added to the compaction train.

2.5.2 Edge cracks

Photo 2-3 shows edge cracks that are longitudinal resulting from the lack of shoulder support at the pavement edge. Settlement of the base soils, poor drainage, and frost heaves are other causes (Ministry of Transportation Ontario, 1989). There is also lateral movement when using steel drum rollers to compact asphalt mats at unsupported edges, resulting in poor edge finishing.

Photo 2-3 Edge crack

2.5.3 Construction joint

Photo 2-4 shows a typical centerline joint failure caused by the intrusion of air and water, which results in a combination of low density, permeability, segregation and lack of bonding at the interface (Ministry of Transportation Ontario, 1989).

Photo 2-4 Centerline crack

Longitudinal joint construction and compaction is encountered during asphalt pavement construction when a lane is constructed adjacent and parallel to a previous lane. For a joint to be hot, or a cold typically depends on the temperature of the adjacent, parallel hot mix mat.

According to Kandhal et al., (1997) the most common distresses at the longitudinal joint are cracking and raveling caused by low density and surface irregularity. Improperly constructed joint accelerates premature deterioration at the longitudinal joints (Pavement Interactive, 2018). Enhanced techniques for longitudinal joints based on paving operation and joint construction devices are echelon paving, joint heaters, wedge joint, cutting wheel, joint adhesive and sealant (Pavement Interactive, 2018; Ministry of Transportation Ontario, 2008). Road authorities avoid specifying costly joint techniques as a standard in the contract because applying them increases paving costs, time, and construction staging issues (Ministry of Transportation Ontario, 2015). Hence, there is a need to enhance compaction method which will result in more uniform density across a longitudinal joint without additional cost and therefore, minimize or eliminate cracking and raveling problems at the joints.

To summarize, the CCM roller circular shape and the choice of hard steel material to compact a soft layer on top of a rigid base layer results in an unstable system due to relative rigidity. Moreover, CCM roller produces short duration pressure pulse stress on asphalt mat during the compaction process. The mat resists the roller pressure with a high elastic stiffness. These CCM method roller design flaws cause surface defects like construction cracks, poor compaction, and loose asphalt mat texture.

The surface deficiencies left by current rollers aid other deficiencies such as stripping, fatigue and thermal cracking (Abd El Halim et al., 2013). Poor compaction at centerline joint and unsupported edges are very common that road authorities avoid testing of quality in these locations (Shaw et al., 2015). There are techniques available currently to improve joint and unsupported edges but adopting them will increase the paving cost. Road authorities also avoid specifying costly joint techniques as a standard in the contract to reduce contract cost.

Deficiency in the compacted mat has been recognized for more than 50 years but the real cause

for the defect which is the roller design flaws was unreleased until 1985. It is unfortunate that despite knowing the cause for the surface defects over 30 years highway pavement construction industry have not acted to eradicate the old problems like construction cracks that still exist due to the use of the CCM method. Additionally, disregarding design flaw has led to other rollers being added to the compaction train. This allowed increasing in construction and maintenance costs of asphalt mat for over thirty years which will be evaluated in detail later in this thesis.

2.6 History of the AMIR roller

2.6.1 AMIR compaction technology

Abd El Halim (1985) observed that the CCM steel roller induced construction cracks, due to conflicts of their drum geometry and stiff composition with the soft flat asphalt layer according to the concept of relative rigidity. He proposed a compaction concept to eliminate construction cracks by replacing the material of the roller and modified the geometry of the roller to allow compaction of soft asphalt without causing surface cracks. The innovative design improved the compaction of unsupported edges. Abd El Halim created his compaction concept by inventing the ASPHALT MULTI-INTEGRATED ROLLER TECHNOLOGY prototype: AMIR roller. This roller uses a multi-layered rubber belt to create a single flat contact area for compaction. The belt is flexible, it provides a closer rigidity match to the softer asphalt layer and does not cause any surface cracks during its use.

The AMIR technology was tested in several field trials in Egypt 1986, Canada from 1989 to 2006, and in Australia from 1997-2006. The detailed compaction and permeability results observed in the three countries have been compared to CCM in numerous papers including Abd El Halim et al., (2006) and Richards et al., (1999). However, a brief review of the major conclusions of these trials is beneficial, as they are comparable with the present study.

Early research determined that the AMIR compacted sections had construction crack-free surface with tighter texture. Permeability tests performed in Canada and Australia indicated that sections compacted with the conventional equipment were between two to ten times more permeable than the AMIR compacted sections. Furthermore, the AMIR achieved higher and better uniformity of the density distribution and indirect tensile strength than the CCM. In addition, the AMIR eliminates the CCM necessitated additional independent rollers of breakdown and finish.

To summarize, the AMIR compaction method does not produce construction cracks and improves joint compaction by changing the CCM geometry and composition. However, the AMIR compaction technology was not widely used in the construction industry before or during this study, which could be due to insufficient information about its optimal compaction values, adaptability in bridge deck asphalt pavement compaction, economic benefits and long-term performance of the compacted surface. As previous studies of the AMIR were not sufficient to provide the above key information to the construction industries, it was important to have the participation of a Canadian paving contractor and MTO to illustrate the suitability of the AMIR roller to provide asphalt roads with better long-term performance. Taking these major steps was essential to provide the data and information that will allow the highway construction industry to recognize the technical and economic benefits of the AMIR compaction method, which are discussed and presented later in this thesis.

2.6.2 Status of the AMIR roller

In 2012, the MTO in collaboration with Carleton University initiated a research program to upgrade the AMIR I roller. The upgraded roller (AMIR II) incorporated a steering unit that allowed it to maneuver or turn sideways, a function unavailable in the earlier version. Other major upgrades included replacement of the rubber belt with Teflon to avoid asphalt picking and improved hydraulics through a self-regulating hydraulic system to maintain optimal tension on

the compaction belts. Several in-house trials in Tomlinson yard (Rideau and Green belt) and provincial highway trials (HWY 2 S, HWY 7, HWY 28, HWY 34, HWY 401, HWY 417 and HWY 520) for the MTO were made using above modifications. Due to the proven potential and longevity of the AMIR prototype, several additional enhancements and mechanical repairs were made throughout the course of the trials.

The MTO's interest in improving highway service life and the capability of the AMIR has generated interest to adopt the theory within the Ontario highway construction industry. As a result, a major Ottawa highway construction firm R.W. Tomlinson Ltd, collaborated with Carleton University to produce a new prototype of the AMIR roller to replace the older one. The roller was completed in 2016. Numerous field trials using old and new AMIR prototype were completed on in-house test sections and on several sections of provincial highways. The results of the trials proved the validity of the AMIR concept and roller.

2.7 Highway construction equipment rental rates in MTO

Major portion of the study trials conducted on Ontario provincial highways. The Ontario provincial standard specification (OPSS) for daily hourly rental rates is OPSS No.127. A short description about the need to reference OPSS No.127 in this thesis is given in this section using OPSS user guide (OPS, 2016) and OPSS (Ministry of Transportation Ontario, 2015). Unexpected work is often encountered during highway construction projects, resulting in extra work and additional time (refer to OPSS No.127, Ministry of Transportation Ontario, 2015). When formulating cost proposals for the extra work, the administrator and contractor are required to use standard rate guides to calculate equipment and operating costs, material and manpower. Challenges typically occur when estimating depreciation, repair and overhaul costs for extra work, as it is difficult to predict the total cost of the equipment acquired during the short duration and whether the equipment is needed on a particular project. The introduction of the

equipment rates through OPSS No.127 created consistency by eliminating disproportion and duplication. The equipment rates through OPSS No.127 have improved the administration and cost-effectiveness of road building, as it serves as a rate guide for calculating equipment cost. The OPSS No.127 is not a static document and rates within it are constantly updated to reflect current industry practices and provide average equipment cost province wide by accounting for regional cost differences, mobilization costs as well as short-term equipment use (Ministry of Transportation Ontario, 2015).

In summary, OPSS No.127 provides daily hourly rental rates for public works in Ontario. It includes key information on the rental costs of items such as pavers ($326.30/ hour), asphalt distribution trucks ($135.65/ hour) and material transfer vehicles ($309.05/ hour). In this thesis, these figures are used to help determine the most economical compaction method.

2.8 Summary of literature review

Since 1970, three rollers have been used to compact asphalt mats of the provincial highways in Ontario. Despite this, longitudinal joint and unsupported edges of the asphalt pavement still receive less compaction and lower densities than mat density (Hughes C. S., 1989). The three rollers methodology is supported by the fallacy that the pneumatic roller can remove construction cracks and static steel roller can remove tire marks produced by vibratory and tire rollers. However, increased time, manpower, continuous early deterioration and visible transverse cracks and potholes that continue to grow year after year in addition to rising costs of the road maintenance and carbon emissions make justifying continued use of three rollers difficult.

Numerous studies by Abd El Halim et al., (1985,2006,2016) identify that there are several reasons for asphalt pavement deterioration, one of which is related to deficiencies in the roller design that induce construction cracks formed at the top surface which propagates downwards. The depth of crack propagation varies depending upon timing and effectiveness of maintenance

treatments (Ferne, 2005). The design deficiencies of rollers result in pavement distresses such as cracks, low compaction at unsupported edges and longitudinal joints. These factors were not recognized for more than half a century.

Permeability research work showed that it was important to understand how tight the compacted pavement mat and how much water is passes through the compacted asphalt pavement. A higher percentage of in-place voids and construction cracks allow water to penetrate through the pavement layer. Water in the pavement structure leads to the weakness of pavement and a variety of issues, including stripping of asphalt from the aggregate and freeze/thaw damage. At the time of writing, there was no standard test or reasonable limits for permeability in the Province of Ontario for the field compacted asphalt pavement. It was interesting to note that several projects in USA tried to establish permeability limits to be met in the field but failed (Christopher, 2009; Maupin Jr, 2010).

The literature suggests more information about the AMIR capabilities is required and this study addressed the need by highlighting the technical and economic benefits that can be realized with more widespread use of the AMIR. Provincial highway and in-house field trials performed side by side with the AMIR and CCM methods for flexible pavement (granular base) and bridge deck asphalt overlay (concrete base) as well as three to six years term performance reviews are incorporated into this research. This study will discuss the comprehensive performance of both methods, in order to understand the following: 1) the quality and interaction of the compacted pavement, 2) the optimal compaction data of the AMIR method, 3) comparison of the long-term performance of both compaction methods for 3 to 6 years. 4) a mathematical model to predict the influence of compaction method on performance and permeability, and 5) the most economical compaction method of the two methods.

Chapter 3 : Outline of experimental investigation

To project the long-term benefits of the AMIR technology, it was important to perform comprehensive field and laboratory experimental investigations. The main objectives were to: 1) determine the quality of AMIR compaction and compare it with current achieved quality levels; 2) ascertain the optimum compaction specification for the AMIR roller; 3) understand the economic benefits of the AMIR method compared to that of the CCM; and, 4) observe and determine how asphalt pavements compacted by the CCM and the AMIR technologies compare over a reasonable period of time. This chapter describes the components and activities involved in the experimental investigations of the research plan. Furthermore, the chapter explains the control measures used to avoid bias and discusses the procedures for sampling and data extraction. The investigation consisted of three phases: Phase I was field testing and data collection, Phase II dealt with laboratory testing and Phase III analysis.

3.1 Trial locations

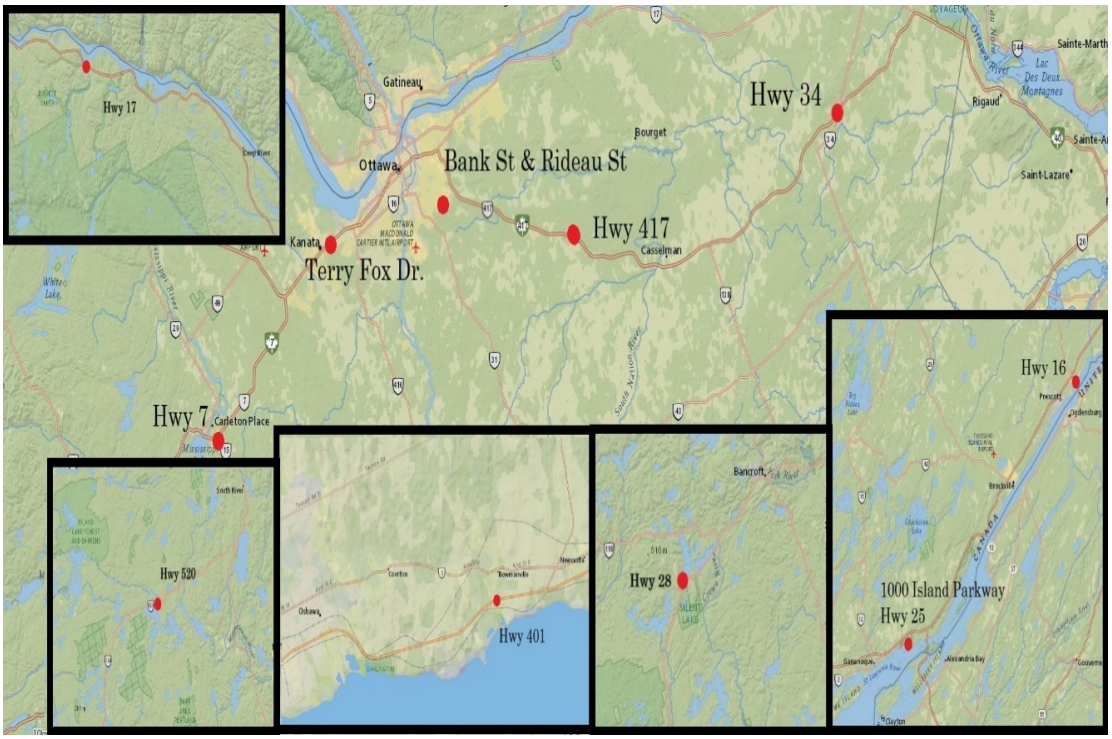


Photo 3-1 Satellite picture of the trial locations

Table 3-1 Trial Location

Location	Trial date (month/day/year)	Roller types	Trial type	Base type
Tomlinson yard	6/25/2012 10/24/2014	AMIR/CCM	In-house	Granular
HWY 2 S	7/24/2012	AMIR/CCM	Provincial	Overlay
HWY 28	9/ 13/2012	AMIR/CCM	Provincial	Overlay
HWY 17	9/25/2013	CCM	Provincial	Overlay
HWY 16	9/27/2013	CCM	Provincial	Overlay
HWY 417	9/29/2013	CCM	Provincial	Overlay
HWY 34	11/27/2014	AMIR/CCM	Provincial	Concrete
HWY 401	9/18/2015	AMIR/CCM	Provincial	Concrete
HWY 7	8/07/2015	AMIR/CCM	Provincial	Concrete
HWY 520	12/ 01/2015	AMIR/CCM	Provincial	Concrete
Tomlinson yard	9/ 21/2016	AMIR/CCM	In-house	Granular
Local Rd	11/15/2017	AMIR/CCM	Municipal	overlay

Photo 3-1 and Table 3-1 shows trial locations. The Table 3-1 also reveals roller types and pavement base types for this study, in chronological order by trial dates. The location, equipment and necessary funding for the trial was provided by R.W. Tomlinson Limited, MTO, NSERC and Carleton University. The MTO identified field test sections in the regions of Barry's Bay, the 1000 Island Parkway and Peterborough to test granular base and bridge deck concrete base asphalt overlays, on Provincial Highways (HWY) 2 S,7,28,34,417,401,520 and local road (Didsbury road). For this research study, the internal trials of AMIR to determine optimum requirements of the roller in a controlled environment will be known as the 'in-house' trials. The R.W. Tomlinson Limited supplied the equipment and necessary materials and identified in-house trial section areas in the Ottawa region at their Power Rd (Rideau Quarry) and Albion Rd (Tomlinson Greenbelt yard).

3.2 Site preparation

This section is written following the MTO specifications and manuals. The construction of asphalt pavement for trial locations in the MTO highways was performed by milling and overlaying 50mm of surface course hot mix asphalt over the existing binder surface. Cold milling scarification was used to salvage pavement material in the MTO study locations. A self-propelled milling machine performed the milling using a rotating drum and a special blade known as a 'tooth'. The teeth and automatic sensors in the milling machine helped to achieve a predetermined depth of pavement and reduced the size of re-claimed material. The hydraulically controlled drums maintain road profiles and the depth of the cuts. The surfaces of the milling areas at the trial locations were clean and dry with uniform grades and cross slopes. No padding or levelling course was required, since the milling surface at all trial locations was rut free.

An SS1 one-to-one emulsion of asphalt and diluted water was used tack coat to bond the binder to the surface course. A thin, uniform layer of the emulsion was applied to all contact surfaces of the existing asphalt surface according to OPSS No. 308.05.1 (Ministry of Transportation Ontario, 2015), at a rate of 0.35 kg per square meter. The application rate was monitored to avoid slips and flushing, and the paving did not begin until the emulsion was either broken or set. Breaking or setting of emulsion was indicated by its color changing from brown to black. Paving started once the emulsion was set.

The compaction method for all the granular base asphalt pavement trial sections for the MTO highways was conducted with three different types of compactors: 1) a heavy vibratory steel roller to provide the compaction required to reach the desired density; 2) a multi-wheeled rubber tire roller to treat the cracked surface; and 3) a light static steel roller to remove roller marks and finish the paving operation. AMIR prototype is a single roller that was shown before to have met

the performance requirements of the study and its performance is compared to the current industry practice of using three rollers to achieve the objectives of this thesis.

Asphalt mixture laid over a bridge deck is considered as a concrete base asphalt overlay for this study. The bridge deck trial location surfaces received two lifts of 40mm asphalt over the protection board that waterproofs the surface of the bridge deck slabs. The asphalt overlay is much thicker on the approach slab areas. The SS1 emulsion is applied at a rate of 0.5kg per meter over the protection board, as recommended by OPSS No. 308.5.1 (Ministry of Transportation Ontario,2015). The application rate was monitored, emulsion was allowed to set. Paving started as soon as the emulsion was set.

The OPSS No. 313.07.10 (Ministry of Transportation Ontario, 2015) MTO specification for paving on bridge decks was followed for the laying and compaction of asphalt on the bridge decks. According to the specification, the roller used must be of a minimum mass of 10 tons and vibration free. Currently, a non-vibrating steel roller weighing a minimum of 10 tons and a rubber tire roller weighing minimum mass of 18 tons often are used for compaction. The weight of the AMIR II roller is 10 tons and it operates without vibration, which conforms to the specification. To assess performance, the trial sections were compacted using the AMIR II side-by-side with the conventional or current compaction method (CCM), to ensure that positive or negative outcomes would be due to the rolling machines, rather than to external factors such as mix design or subgrade. For this study, the CCM are also known as the 'Control', and the AMIR II method as 'AMIR'. Trial areas for the study on MTO highways for each compaction method were a minimum of 500m by 4.25m for flexile pavement, and a minimum of 100m by 4.25m for concrete based pavement.

Construction of asphalt pavement for the in-house trials was performed by placing hot mix asphalt over the existing surface, without a base or sub-base course. The in-house trials are used

to determine rolling patterns, compare the performance of the CCM roller vs AMIR, assess the AMIR compaction quality at different temperatures and thicknesses of asphalt mixture, and tune the AMIR roller. The areas of the in-house trial mats varied.

3.3 Field testing

Phase I of the experimental investigation involved performing site examinations of finished surfaces, conducting permeability tests and to extract 150mm field cores from the compacted mat at the trial locations. The recovered cores were taken to the Carleton University Civil Engineering Laboratory for further testing. To avoid personal bias, the test points were randomly selected along and across the trial sections by following the MTO 2006 field guide for the acceptance of hot mix and waterproofing. Permeability testing is not recognized as a standard test procedure to check the quality of compacted asphalt surface by the MTO and is not a specified requirement in their work projects. Measurement of onsite permeability assesses the infiltration of moisture due to the open texture of a compacted surface and highlights the influence of construction cracks induced by the current rollers. For this study, the National Centre for Asphalt Technology (NCAT) permeameter was used to perform the permeability testing at all trial locations. The falling head type permeameter from Gilson Company Inc. shown in Photo 3-2 was used in the field to examine the quality of compaction in terms of achieving less permeability values through the utilization of the CCM and AMIR compaction methods.

The permeameter consists of four tiers of different diameters on a continually graduated standpipe. The time taken for the drop-in water levels from the top to the bottom of each tier is recorded. The test considered complete, when the level is stable at a specific mark or when the rate flow is slow. The drop-in water level was recorded carefully, as this process was executed slowly due to the increase in diameter of the standpipe in each tier.

The coefficient of permeability is calculated using equation 3-1 (Allan, 1999) .

$$"K = "((a*I)/(A*t))*\ ln(\ 〖\ h〗\ \_1/h\_2\ ) \quad (3\text{-}1)$$

Where;

K = the coefficient of permeability (cm/sec)

a = the internal cross-sectional area of the standpipe ($cm^{2)}$

I = the thickness of the asphalt layer (cm)

A = the circular cross-sectional area of the tested pavement (cm^2)

t = the elapsed time between h_1 and h_2 (sec)

h_1 = the initial head (cm)

h_2 = the final head (cm)

Photo 3-2 Phase I: Permeability testing

Immediately after extraction, each core was numbered using a highway or alpha numeric numbering scheme, and the compaction type was assigned as a control to prevent misrepresentation. For example, HWY 28-A 2 means Highway 28 AMIR compacted core sample number 2. The top surface of the extracted core is smooth, and the bottom surface is not

even. The core was placed in a box with the bottom surface oriented upwards to avoid transportation damage. The core box was then transported to the Carleton University Civil Engineering Laboratory for Phase II investigation. Subsequent Photos 3-3 and 3-4 show the extraction of field core.

Photo 3-3 Phase I: In-house core extraction

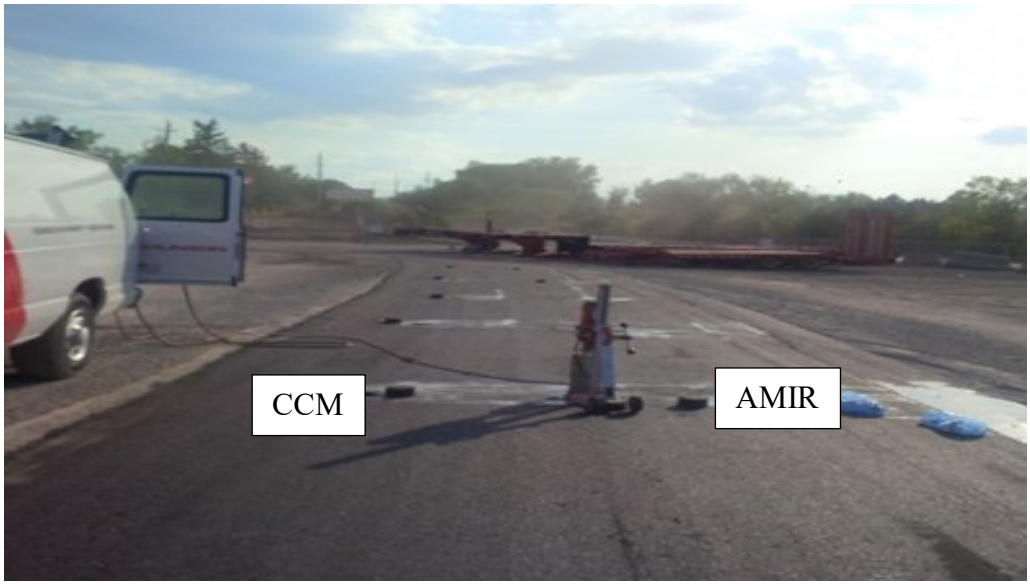


Photo 3-4 Phase I: In-house extracted cores

Subsequent Photos 3-5 and 3-6 show the surface conditions and textures of compacted asphalt surface using both compaction methods.

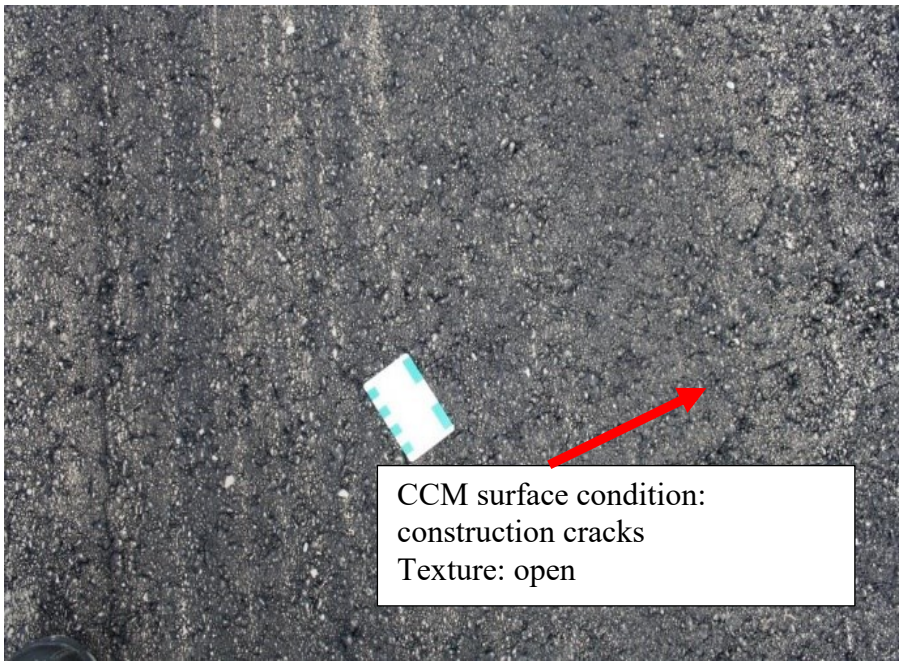


Photo 3-5 In-house CCM surface texture

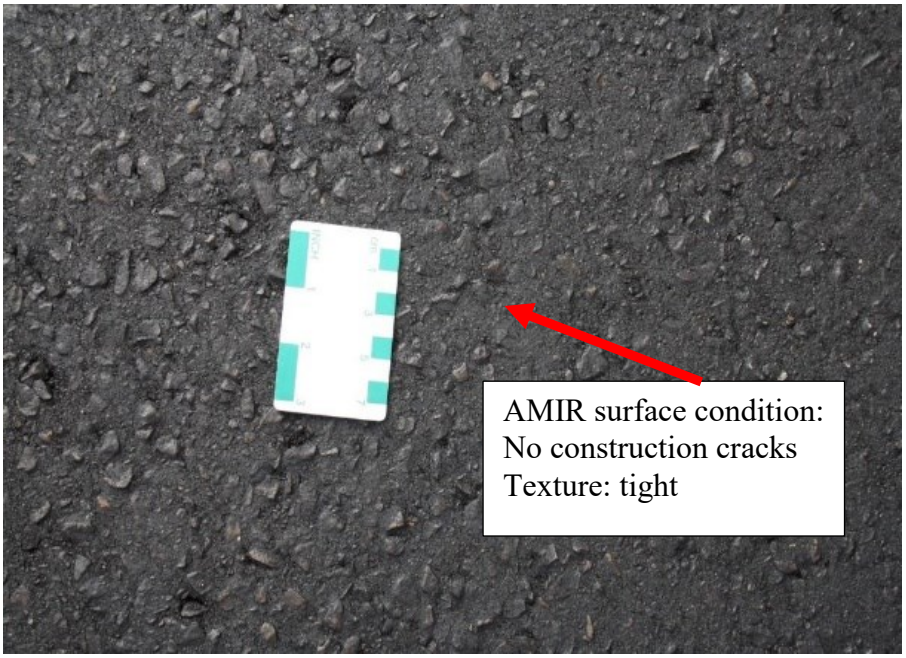


Photo 3-6 In-house AMIR surface texture

Falling Weight Deflectometer (FWD) is a device used to evaluate pavement structure strength by measuring a desire applied load vertical surface deflection on a pavement without damaging or destroying pavement surface (Richard Kim, 2002). Road authorities use values obtain from

the FWD test for selecting rehabilitation alternatives (Ministry of Transportation, 2013). There are several options of FWD equipment available on the market. A Dyna brand FWD was used for measuring pavement strength in the trial section of the Tomlinson yard following a deflection basin test. Standard elements of a Dyna brand FWD are deflection sensors and load plates (Ministry of Transportation, 2016). Number of available deflection sensors in equipment varies. The equipment is available in either a trailer or truck mount. The load plate is dropped at specific height on the test point the impact is transmitted to the pavement through a circular plate that creates a dynamic load impulse which simulates actual load by moving vehicle on a pavement. The pavement deflection resulting from the drop measured by sensors known as geophone spaced at predetermined intervals from the loading plate recorded into a microcomputer. The recorded pavement response is used to analyze surface modulus of the pavement structure.

Photo 3-7 Falling Weight Deflectometer

The surface modulus calculated using measured surface deflections based on Boussinesq's equation given below (Richard Kim, 2002):

$$E\_o = 2P(1 - \mu^2)/(\pi r D\_r) \quad (3\text{-}2)$$

Where,

E_o = Surface modulus in MPa

P = applied load in N

μ = Poisson's ratio assumed as 0.35

r = is the distance from the center of the applied load in mm

D_r = deflection at distance r from the center of the applied load in mm

3.4 Laboratory testing

The purpose of Phase II is to obtain key measurements from the extracted field core, namely: laboratory permeability, core thickness, bulk relative density and percent compaction values were measured. The bulk relative density value for the extracted core obtained following LS 232 procedure (Ministry of Transportation Ontario, 2010). The extracted core cleaned with a wire brush to remove contamination and loose material and allowed to air dry for 24hours to remove moisture. The moisture free core sample is then measured for dry weight (A), in water (B) and saturated surface dry weights (C) using a minimum of 1000 gram scale with a precision to 0.1gram. The relative density of the core calculated using equation (3-3).

$$Bulk\ Relative\ Density = A/(B - C) \quad (3\text{-}3)$$

Where;

A = weight of specimen in air (g),

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

C = weight of specimen in water (g).

Following LS 264 procedure an asphalt mixture specific gravity without air voids is multiplied

by density of water to obtain theoretical maximum relative density (MRD) in the laboratory.

The theoretical maximum relative density (MRD) of an asphalt mixture calculated using equation (3-4).

$$\text{MRD} = \frac{D-E}{(D-E)-(G-H)} \quad (3\text{-}4)$$

where:

D = mass of beaker and mixture in air, g

E = mass of beaker in air, g

G = mass of beaker and mixture in water at test temperature, g

H = mass of beaker in water at test temperature, g

Percent compaction of the core for this study is measured from the obtained bulk relative density of the core and using mix design theoretical maximum relative density as shown in equation (3-5).

$$Percent\ compaction = (BRD/MRD) * 100 \quad (3\text{-}5)$$

Where;

BRD = Bulk Relative Density

MRD = Maximum Relative Density

The MTO uses percent compaction of the core as the key measure to control in-place air voids or in-place density by specifying a percentage of the theoretical maximum relative density in order to accept or reject a compacted asphalt mat along with thickness, asphalt mix properties and smoothness

The core tensile strength is measured at room temperature using an INSTRON series 5583 loading machine. The load is applied by placing the core between two steel strips parallel to the core diameter and loading uniform compression on the steel strips perpendicular to the core length. This causes the core to fail by splitting along its vertical diameter. The maximum load is

recorded, and indirect tensile strength (IDT) is determined as shown in equation (3-6).

$$S_t = (2000 * P)/(\Pi * t * D) \quad (3\text{-}6)$$

Where:

S_t = IDT strength (kPa)

P = maximum load (N)

t = specimen height immediately before testing (mm)

D = specimen diameter (mm)

3.5 Analysis

In addition to comparing the field and laboratory test results it was important to develop a mathematical model to identify whether performance and permeability can be related to the compaction method used. Cost estimation to identify the most economical compaction method between AMIR and CCM using MTO rental rates from the OPSS No.127 (Ministry of Transportation Ontario, 2015) and Statistics Canada 2016 Labour Rates (Statistics Canada, 2016). The MTO accepts one-year term general warranty of workmanship and quality from contractors (see general condition, section 7, subsection 8.02 in OPSS No.100 (Ministry of Transportation Ontario, 2015). In this study, performance assessments of the granular base and concrete base of the asphalt pavements were limited to a maximum term of six years which exceeds the current requirement of the general warranty provided by the contractors to the road authorities. Thus, the outcomes of the performance reviews of compacted mat in the trial sections will provide effective results.

3.6 Summary of experimental outline

To summaries, the key values such as bulk relative density, percent compaction and indirect tensile strength were calculated using the extracted cores from the field trial site. Water infiltration amount and pavement structural strength of the field trial were measured on

compacted asphalt mat using National Centre for Asphalt Technology (NCAT) permeameter and Falling Weight Deflectometer (FWD), respectively. OPSS No.127 and Statistics Canada 2016 labour rates used to determine the economic differences between the compaction methods of AMIR and CCM, in terms of equipment, manpower and time. Performance reviews of the trial sites to determine long term quality of the compacted surface using two compaction techniques (AMIR and CCM) limited to a maximum of six years.

Chapter 4 : Development of specifications and optimization of AMIR compaction

This chapter will summarize the findings obtained from the comprehensive study. It will also demonstrate that the performance achieved by the compaction equipment is not attributed due to chance. Through interpreting the results obtained in phases I (field) and II (lab) of the experimental plan, and the direct relationship of the compacted pavement property by two compaction methods, a conclusion was reached about the compacted property. Previous compaction studies stopped at the phases I or II of this study's experimental plan. This study is extended to better understand the economic benefits and performance of the compacted asphalt mats using AMIR and CCM.

This devoted chapter consists of six sections. The first four sections illustrate and study the asphalt pavement properties such as percent compaction, asphalt layer strength, permeability and strength that were obtained from two compaction techniques on two types of base from twelve different sites. The fifth section presents the AMIR compaction method's optimum requirement for asphalt compaction. The final section explains the variance between the compaction methods of CCM and AMIR through real performance, which was obtained as a result of six years of performance observation.

4.1 Percent compaction of two compaction techniques

This section presents and investigates compacted pavement properties namely the percent compaction results obtained from phases I and II of the experimental plan from the trial sites. A total of 12 compaction trials took place in Ontario. Out of 12 asphalt pavement projects, nine trials were on provincial highways, two were in-house and one was on a municipal road. The field investigations began during the summer months of 2012 and continued until the late fall of 2017.

This research is the first in the world to propose and examine the use of AMIR technology for asphalt overlay compaction on a concrete bridge deck. The AMIR method is an excellent replacement for the controversial CCM method due to the lightweight, vibration free compaction technology applied by a single roller. That is something that the previous research studies from the 1990s failed to investigate.

Of the available 12 sites, eight trial sites are common projects where both compaction techniques were used. Four sites are standalone projects. A project is considered standalone if it utilized only one compaction method. Three standalone sites used the CCM, and one used the AMIR method. Only the common projects, where two compaction techniques were used will be discussed in this section. The standalone projects that took place on HWY 16, HWY 17 and HWY 417 using the CCM were used to identify the common problems of construction cracks, loose texture, poor centerline and unsupported edge compaction. These were discussed briefly in the literature review portion of this study. The HWY 34 provincial road trial is the only standalone project that used the AMIR compaction method. It will be discussed in depth later in this study.

In this study, percent compaction is analyzed in order to draw conclusions about the compacted pavement properties. Following Figure 4-1 summarizes the mean percent compaction achieved by the two compaction methods in all trial sites that were tested side by side in both the granular base and concrete base.

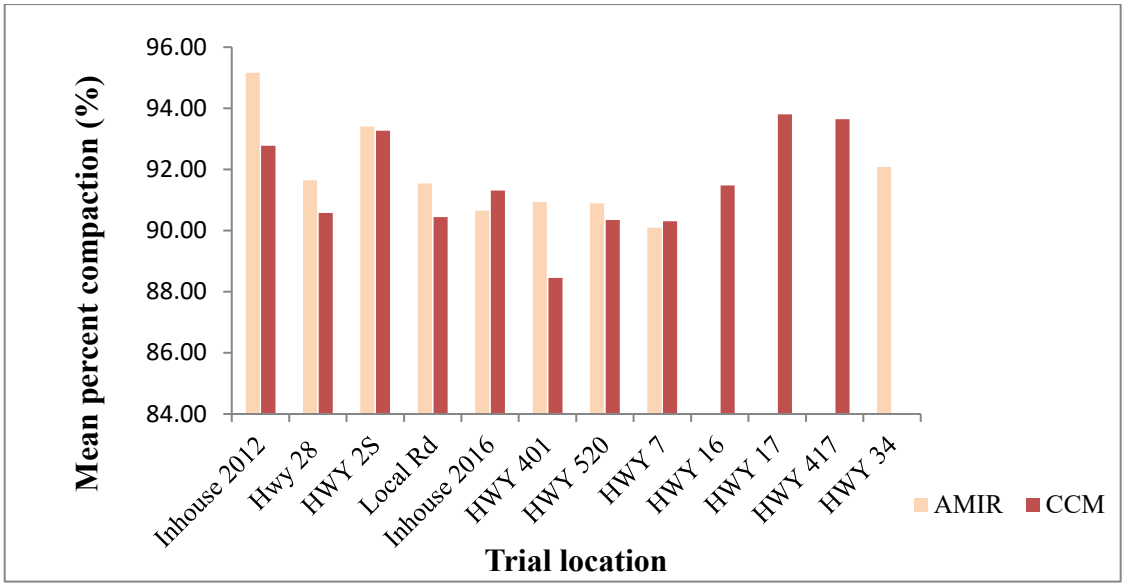


Figure 4-1 Summary of percent mean compaction of the trial locations

The rationale for choosing percent compaction was because the test trials were conducted in various locations using different asphalt mixes and base types. Hence, bulk relative density could not be set as standard due to variation in density of the trial site aggregate. On the other hand, percent compaction result is the measure of density with respect to theoretical maximum relative density (MRD). The standard unit of compaction achieved typically expressed in percentage, which helps to make easy comparisons across the trial section mixes or pavement base types. The MRD of an asphalt mixture acquired through standard testing procedure of LS264 (Ministry of Transportation Ontario, 2010) by multiplying theoretical maximum specific gravity by the density of water. The theoretical maximum specific gravity of an asphalt mixture is the specific gravity excluding air avoids.

The highway construction projects overseen by the MTO usually involve large quantities of asphalt mat (Auditor General, 2016). The MTO uses the mix property of the field sample and the percent compaction of the field extracted core samples to assess the quality of the construction materials received. The percent compaction of a freshly laid asphalt mat presently checked instantly with help of a calibrated nuclear gauge without delaying the project. The core

percent compaction represents the true value of the actual compacted mat used as the final value for all the MTO related project approval. Reference to the above statement can be found in OPSS No.310 section 8 subsection 4 (Ministry of Transportation Ontario, 2015). Setting a minimum percent compaction thru specifications helps the agency (MTO) to control in-place air voids and. This leads to improved mixture durability and pavement service life to achieve a standard quality for their entire provincial road network. The mean percent compaction requirements of the MTO work project shown in the next page Table 4-1. Source for Table 4-1 refer Ontario Provincial standard specification 310. Toronto, service Ontario publication. November 2015, pp21.

Table 4-1 MTO percent compaction requirements based on maximum relative density (OPSS 310, November 2015, pp 21)

Mix Type	Minimum compaction (%)
HDBC	91
Superpave 19 & 25	91
All other mixes	92

To understand the quality of compaction produced during the trial, a comparison of mean percent compaction achieved by both methods with respect to the MTO minimum compaction requirement presented below in the subsequent Figure 4-2. Combined average percent compaction achieved in the granular base pavement by both methods is 92.08% and in the concrete base asphalt overlay pavement the average is 90.15%. According to the Table 4-1 of this study, the acceptable limit of the percent compaction for a wide range of Superpave asphalt mix is 92%.

If we compare the information above with the minimum compaction requirements set by the MTO, it shows that the asphalt pavement compaction on the granular base by both methods meets the MTO requirements, but the compaction of the asphalt overlay on the bridge deck (concrete base) does not. Further analysis is needed to understand the reason for this.

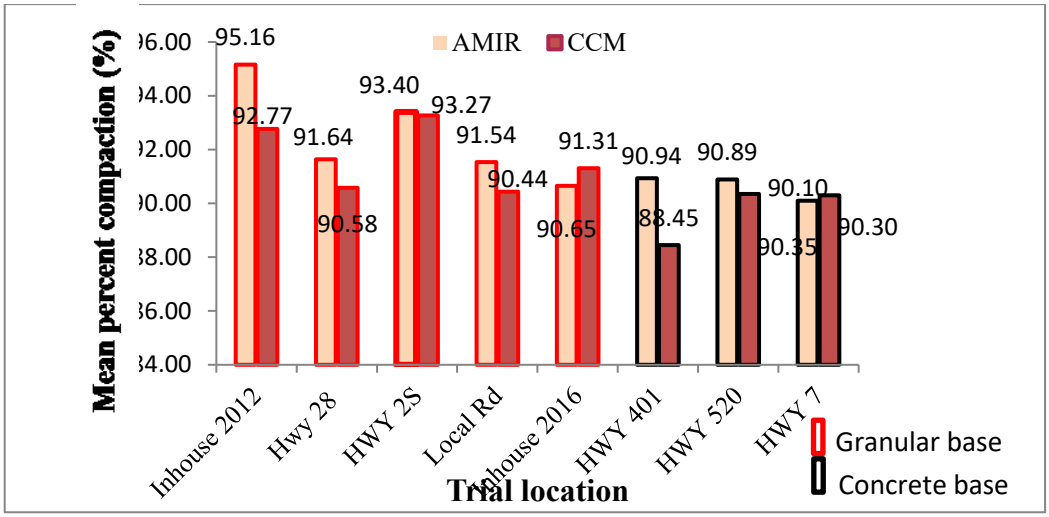


Figure 4-2 Summary of mean compaction results of common trial sections

The subsequent Figure 4-3 summarizes the mean percent compaction achieved by the methods of AMIR and CCM on the granular base asphalt pavement. When compared with the MTO percent compaction requirements (92%), the HWY 28 percent compaction achieved from the methods of AMIR and CCM were short by 0.36% and 1.42% respectively, Didsbury road (Local Rd) was short by 0.50% and 1.70% respectively, and the in-house 2016 trials were short by 1.47% and 0.75% respectively.

Even though the percent compaction was below than the standard requirement, the percent compaction achieved by both roller types is marginally close. The reason for the poor compaction in the HWY 28 may be due to the lower temperature of the asphalt mixture that was received at the site because of its distance from the asphalt mixing plant. In case of Didsbury Road (Local Rd) the lower compaction was due to a steep grade and poor base.

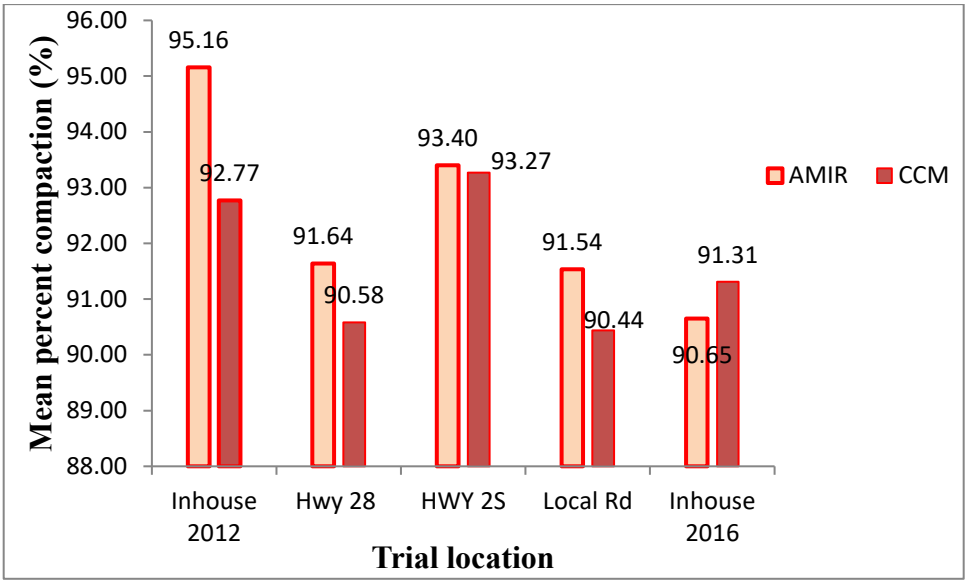


Figure 4-3 Summary of mean compaction result of granular base

In the case of the in-house trial, lower compaction was due to mandatory control of pavement thickness, temperature and rolling passing. The mandatory control testing method used in-house compaction was essential to understand the optimum compaction requirement of the AMIR technique. The overall percent compaction means derived from the trials in the granular base asphalt pavement for the AMIR is 92.5% (92.5 > 92.0) and the CCM is 91.7% (91.7 <92.0). These results confirm that the AMIR compaction method is better than the CCM.

During field observations, it was noted that to achieve the percent compaction value shown in the following Figure 4-3 the CCM method using three rollers took a combined total of 17-22 passes and the AMIR method took only 8-10 passes. From the above, it is clear that the percent compaction achieved by the two methods on the asphalt pavement is similar, but the effort, manpower and time taken to achieve this is different. The AMIR compaction method took fewer passes and achieved better percent compaction results than the CCM method on the granular base asphalt pavement.

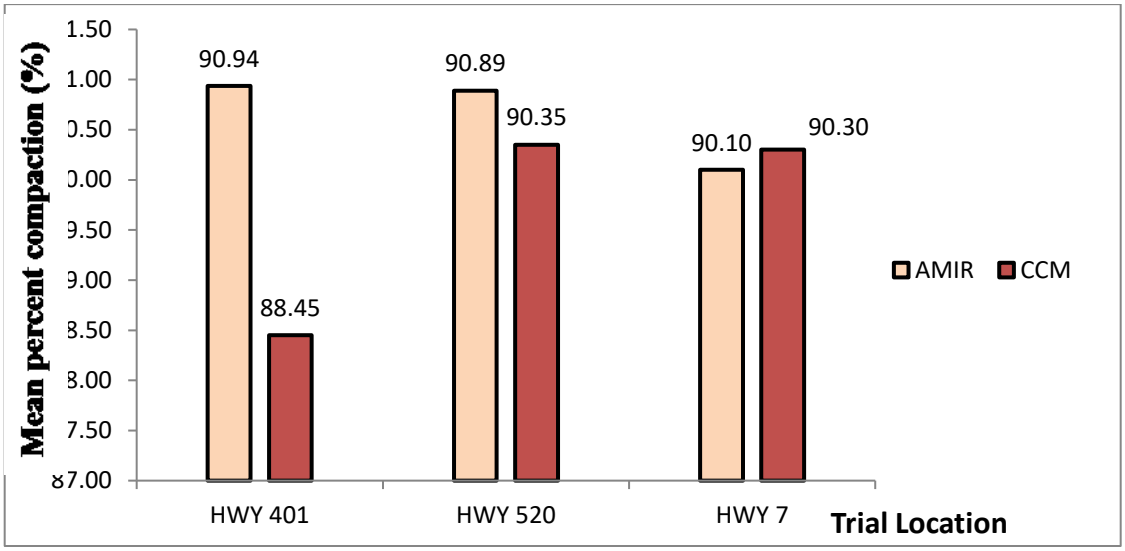


Figure 4-4 Summary of compaction result of concrete base

From Figure 4-4, when compared with the MTO percent compaction requirements, the AMIR compaction method combined percent compaction mean in the concrete base asphalt (bridge deck) overlay pavement is lower by 1.36% (90.64<92.0) while the CCM method is lower by 2.3% (89.7<92.0). Overall, the percent compaction achieved by both the methods fall below to the MTO minimum requirement as mentioned in the Table 4-1. Despite shortfall, the AMIR method still performed better than the CCM method.

From Figure 4-4, it is evident that the AMIR compaction method performed well in most sites. The exception is in the HWY 7 trial site where the CCM method performed slightly better than he AMIR compaction method. Photo 4-1 taken during the site inspection and observation shows separation of aggregate particles from rest of the asphalt mat (segregation) caused by poor workmanship can be attributed to segregation of asphalt mat during the trial and ultimately lowered the value of the AMIR compaction method in the HWY 7 trial.

Photo 4-1 Segregated mat of HWY7 Trial location

During field operations , it was reported that the CCM method's standard vibratory roller is not permitted for use in asphalt overlay compaction on the concrete bridge deck due to the MTO's specification requirement: OPSS No.313 subsection 07.10 (Ministry of Transportation Ontario, 2015). Instead, specific weight and size steel rollers without vibration were required in the compaction train for this purpose and due to construction staging. It should also be noted that these rollers are an additional investment needed by the contractors to compact the bridge deck asphalt overlay when using the CCM method. On the other hand, the AMIR method uses the same roller for the asphalt overlays on both granular and concrete bases because the roller weighs 10 tons and operates without vibration. Therefore, no additional investment in the roller was required in the AMIR compaction method which is a saving to highway construction contractors. Analysis of figures 4-3 and 4-4 demonstrates that the combined mean percent compaction of both methods in the concrete base asphalt pavement (90.2%) is 2.1% lower than the combined mean of the granular base asphalt pavement (92.1%). The lower percent compaction of both the methods on the bridge deck asphalt overlay is due to the influence of construction work practice. The loose asphalt mat on the bridge deck was not compacted at the required compaction temperature of the mix design in all the trial sections due to the presence of a protection board

that secures the waterproofed surface of the bridge deck slab. The contractors laid the loose asphalt mix at a temperature of 135°C to prevent the protection board from burning and laid it slowly to avoid unnecessary movement of the board. Moreover, the MTO bridges consist of two lifts of 40-45mm asphalt. After placing the first lift, the paving crew needs to wait for more than 4 hours until the first or base mat cools down to 50°C before they place the second or top lift over the first to fulfill the OPSS No.313 requirement (Ministry of Transportation Ontario, 2015). In summary, it is evident that both compaction methods are capable of meeting the minimum percent compaction requirement standard set by the MTO. Nonetheless, the resources needed to achieve this objective differ. In order to align with further MTO specifications, additional resources are required for the CCM to compact bridge deck asphalt overlay but the AMIR method already address this within its own design. To conclude, the AMIR compaction method produces better a percent compaction results than the CCM method with less effort, manpower and time.

4.2 Falling Weight Deflectometer

The earlier section explained the percent compaction achieved by the CCM and the AMIR compaction methods on the asphalt pavement are merely similar because of the fixed target value set by the road authorities, but the effort, manpower and time taken to achieve the target value is different. In this section, overall strength of compacted pavement achieved is analyzed using Falling Weight Deflectometer (FWD) test to draw conclusion about compacted pavement properties.

A brief description of the FWD described in Chapter 3. The Tomlinson yard-2012 trial section was used for carrying out FWD tests on one lane of the CCM and two lanes of AMIR for a combined test section length of 25m. The test was carried out one year after the trial site opened to the heavy equipment traffic of the Tomlinson yard. A Canadian firm from the list of MTO

approved FWD testing service, tested the trial section using the Dyna brand FWD device. The trial location was free from frost, debris and obstructions during the time of testing. Deflection measurements were taken along the center of each compacted sections. The load plate center was placed on the test point in the direction parallel to roller pass during compaction. The testing interval of 5m in length was the choice for analysis. The raw data of the FWD in the trial location test point offered normalized deflection information of the pavement structure for three loading sequence 40 kN, 55 kN, and 70 kN. The load was normalized to 40kN which is the equivalent single axle load (ESAL). ESAL is a concept used by the road authorities to determine pavement damage caused by the effects of axles carrying different loads. Device sensors recorded the deflection at 300,450,600,900,1200,1500,1800 and 2100mm from the point where the load was applied, respectively. The surface moduli are calculated from the recorded deflections using equation (2) explained in chapter 3. Omar Abdelalim et al. (2013) have published detailed test results. As both methods can meet the MTO compaction requirement, a short review of the major conclusions of FWD trials is beneficial to understand the difference in pavement strength. Therefore, the test results obtained from one test location is discussed in this thesis. The proceeding graph shows the average deflections at each sensor as well as the surface moduli results. The values closer to sensor 1 represent the strength of the compacted surface while the values further away reflect the strength of the subgrade under the asphalt layer. The results at each sensor are the average readings at that sensor along the 25 m of the test section.

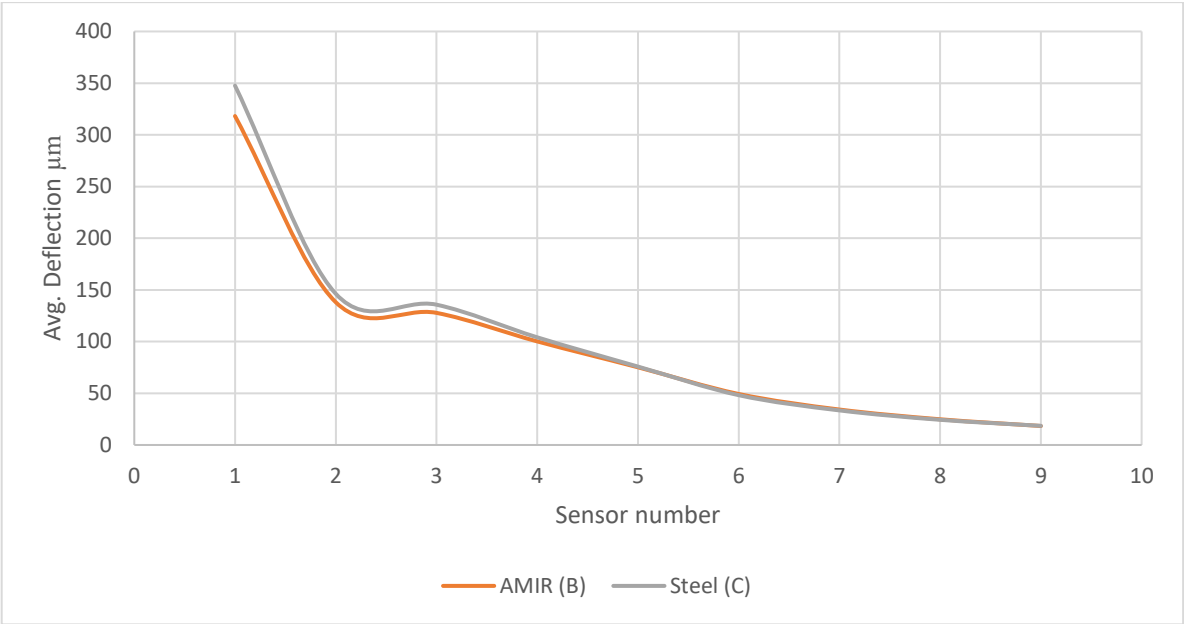


Figure 4-5 Normalized deflection

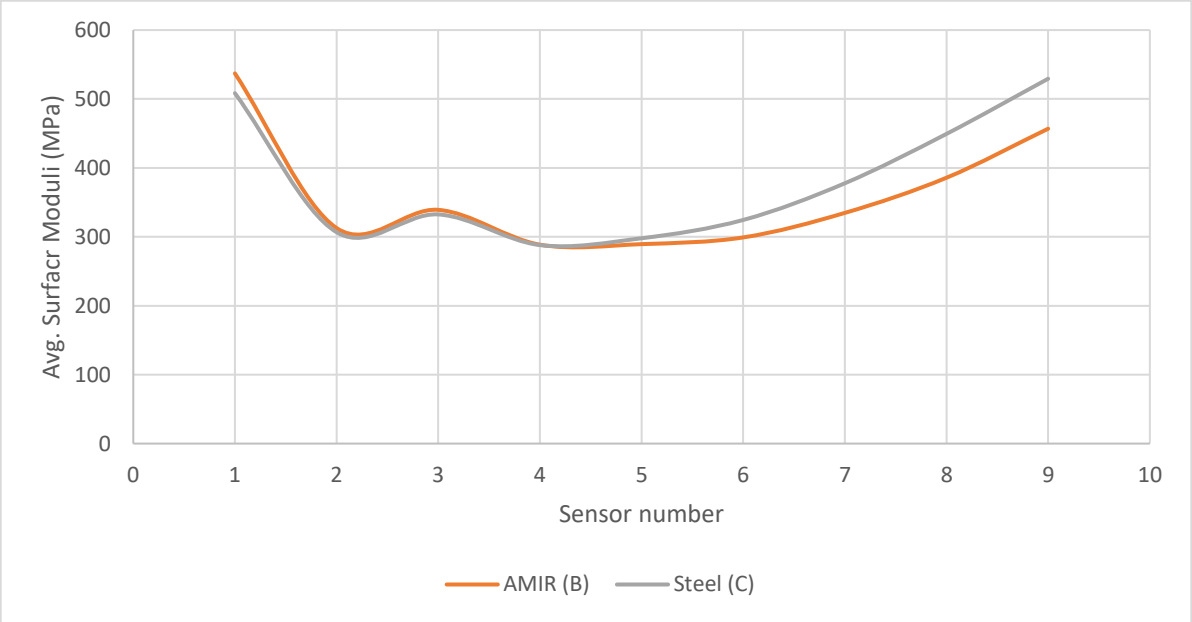


Figure 4-6 Surface moduli

Observations from the deflection graph indicates the CCM (347.6) compacted mat deflection is 9.14% higher than the AMIR (318.2) compacted mat. The surface moduli of CCM are reduced by 5.7% as shown in Figure 4-6. This shows that the compacted pavement properties achieved by the AMIR roller is superior to the CCM. Another important result that can be seen in the figures are the values at sensor number 6 and further (Figure 4-5), there was no significant

difference between the two rollers since the data reflected the strength of the subgrade which is under both the lanes. Finally, the slope of the deflected bowel (Figure 4-6) of the AMIR compacted mat is relatively less steep compared to that of the steel or CCM compacted lane, suggesting that the steel compacted asphalt layer was relatively more stressed for the same applied load.

In summary, the AMIR and CCM methods percent compaction results were similar due to fixed targeted value of road authorities. The effort, manpower, and time taken to achieve by both methods to reach the target value are different. Since both rollers achieved this value, it made it difficult to understand the difference between the two rollers compacted pavement property. The falling weight Deflectometer test results showed that deflection of the asphalt layer compacted by the AMIR roller is 9.1% lower than that of the CCM compacted asphalt layer. A 9.1% reduction in pavement deflection could result in longer service life and or lower rehabilitation costs (Queensland Department of Transportation and Main Roads Pavement, 2012).

4.3 Permeability

How tight is the compacted pavement mat? Permeability testing will help tremendously to properly resolve the prior question by using the observed rate at which an amount of water passes through the compacted pavement. At the time of writing, there was no standard test or reasonable limits for permeability in the Province of Ontario. Permeability testing conducted in the trial locations on both the compacted sections of CCM and AMIR to highlight the practical need for the permeability testing on fresh compacted asphalt pavement. This section of the chapter presents and investigates the compacted pavement property of permeability result obtained from a total of 12 compaction trials that took place between the summer of 2012 and late fall of 2017. A chosen test is considered a “common” when two compaction techniques were used side by side in a specific project. There were nine common projects for permeability carried out in five

granular and four concrete bases. The remaining three projects of permeability were recognized as standalone due to the use of a single compaction technique in the entire project. The mean permeability results obtained from all the sites using the two compaction techniques are presented in Figure 4-7.

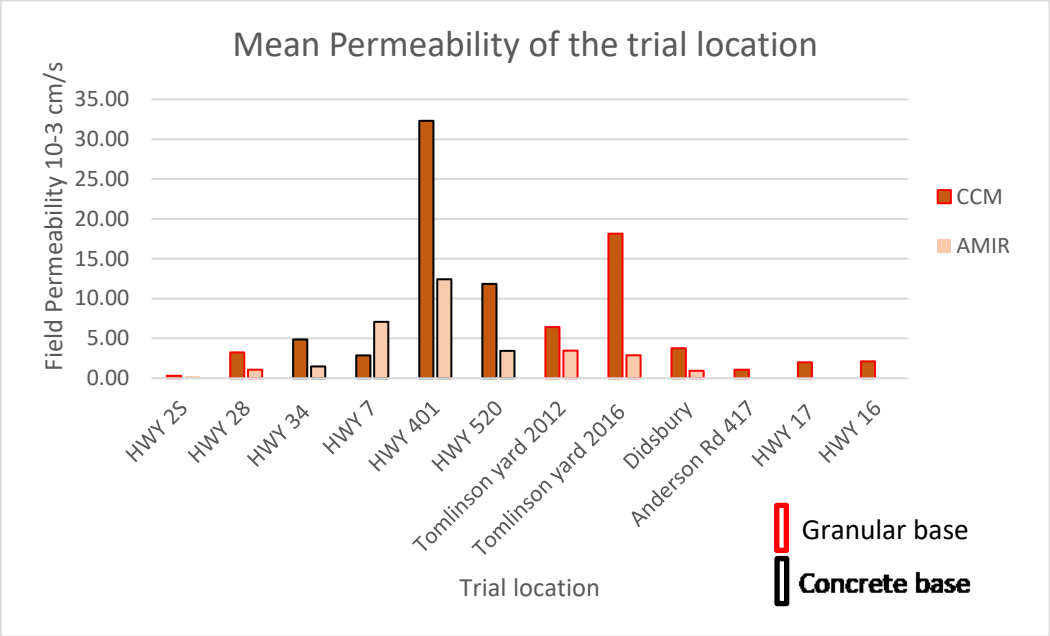


Figure 4-7 Mean permeability result of individual trial locations

From here on only the common projects, where two compaction techniques were used will be discussed in this section. Succeeding Table 4-2 presents the average permeability results from all the granular base trial sites of common projects. The CCM compacted five trial sites average permeability from the table is 6.36 x 10^{-3} cm/sec and the AMIR compacted achieved 1.60 x 10^{-3} cm/sec. The ratio of CCM to the AMIR on the granular base trial sites on average is 4.0.

Similarly, a direct comparison of the average permeability of granular base asphalt overlays from the two provincial highways (HWY 2 S and HWY 28) and two in-house specific trials demonstrates that the AMIR compacted trial sections have lower permeability; an average of 3 times (1.78:0.68) and 4 times (12.23:2.85) respectively over the CCM. These findings complement previous study results of the AMIR roller on the granular bases.

Table 4-2 Mean permeability of asphalt overlay on granular base trial site

Trial location	Trial Highway type	Project type	CCM x10^-3 cm/sec	AMIR x10^-3 cm/sec
HWY 2 S	Provincial	Common	0.32	0.28
HWY 28	Provincial	Common	3.24	1.07
Didsbury	Municipal Rd	Common	3.77	0.94
Tomlinson yard 2012	In-house	Common	6.30	2.81
Tomlinson yard 2016	In-house	Common	18.16	2.89
		Average	6.36	1.60

The following Table 4-3 illustrates test results from the concrete base asphalt overlay trial sites on the bridge deck. The prepared table presents average permeability of the CCM resulted in 12.98x10^{-3}cm/sec and the AMIR 6.00 x10^{-3}cm/sec. The observed ratio of the CCM to AMIR shows that on an average, the trial sites compacted by the AMIR show 50% lower permeability than the CCM.

Table 4-3 Mean permeability of concrete base asphalt overlay trial sites

Trial location	Highway type	Project type	CCM x10 ^-3 cm/sec	AMIR x10^-3 cm/sec
HWY 7	Provincial	Common	2.87	7.08
HWY 34	Provincial	Common	4.87	1.07
HWY 401	Provincial	Common	32.31	12.42
HWY 520	Provincial	Common	11.85	3.44
		Average	12.98	6.00

The permeability value of the AMIR in HWY 7 is higher than the CCM due to segregation caused by poor workmanship and mix design. Due to the project deadline, the trial mat used on the HWY 7 was removed and replaced without the AMIR by the road authority. The findings

from the AMIR compacted sections on the concrete base asphalt overlay coincide with previous studies of permeability results on a granular base reported in the chapter 2. The results in tables 4-2 & 4-3 explain that the AMIR compacted surfaces achieved better permeability than the CCM. Without a set value, it is impossible to know whether the obtained permeability meets the standard that would be needed based on the environment factors and traffic levels.

Table 4-4 Queensland Department of Transportation and Main Roads permeability classification

(Vardanega, P et al., 2008; as cited After waters, 1998)

Permeability (µm/sec)	Permeability (µm/sec)	Category	Description
0.01-0.1	1x10^-6 to 1x10^-5	A1	Very low permeability
0.1-1	1x10-5 to 1x10^-4	A2	Low permeability
1-10	1x10^-4 to 1x10^-3	B	Moderate permeability
10-100	1x10^-3 to 1x10^-2	C	Permeable
100-1000	1x10^-2 to 1x10^-1	D	Moderately free draining
1000-10000	1x10^-1 to 1	E	Free draining

The Queensland Department of Transportation and Main Roads (QDMR), Australia keenly follows the asphalt permeability classification on the fundamental basis of likely consequence, and it is provided in the preceding Table 4-4. Specifying an applicable standard, as the QDMR does, for asphalt highway permeability enables any road authority to maintain consistent values over the entire network. Comparing the permeability results for both granular and concrete bases to the QDMR classification helped to realize the importance of compacted mat performance to a standard.

The subsequent Tables 4-5 and 4-6 indicate that most of the trial sites fall under moderate permeability category “B” of the QDMR classification. HWY 2 S and HWY 401 trials fall under the low permeability category “A2” and moderately free draining category “D” respectively. The direct comparison of these results with the QDMR specifications demonstrates the permeability

value of the trial sites spans a broad range and that there is a critical need for standardization. Therefore, the road authority like the MTO needs to come up with a minimum required permeability level based on traffic volume, environmental conditions and paving material to obtain permeability values that can be consistently applied to the entire Ontario road network.

Table 4-5 Comparison of Granular base test result with QDMR values

Trial location	**CCM x10^-3 cm/sec**	**QDMR Category**	**AMIR X10^- 3 cm/sec**	**QDMR Category**
HWY 2 S	0.32	A2	0.28	A2
HWY 28	3.24	B	1.07	B
Anderson Rd 417	1.06	B		
HWY 17	1.99	B		
HWY 16	2.12	B		
Didsbury	3.77	B	0.94	A2
Tomlinson yard 2012	6.30	B	2.81	B
Tomlinson yard 2016	18.16	D	2.89	B

Table 4-6 Comparison of concrete base test result with QDMR specification

Trial location	**CCM x10^-3 cm/sec**	**QDMR Category**	**AMIR X10^-3-cm/sec**	**QDMR Category**
HWY 7	2.87	B	7.08	B
HWY 34	4.87	B	1.07	B
HWY 401	32.31	D	12.42	D
HWY 520	11.85	D	3.44	B

This specific section concludes that the AMIR compaction method showed reduced permeability levels than the CCM sections. The possible cause for the elevated level of permeability in the CCM section could adequately represent the profound influence of construction cracks induced

by the CCM compaction equipment. The road authorities like the MTO currently rely on the mix property and the percent compaction of the field sample to assess the quality of material received in an asphalt mat. During this thesis writing, there is no standard test or published specification in Canada to assess the permeability of compacted asphalt.

Incorporating nondestructive testing procedures like permeability and setting values for permeability such as the QDMR will represent a substantial addition. Standardized permeability values will help the road authority to predict the paving material and grade required for improving the drainage system of the road network. As a practical consequence, this will improve the long-term performance of the highway road networks.

4.4 Indirect tensile strength

The testing procedure for indirect tensile strength is presented in Chapter 3-2 of this research thesis. The field core is loaded into the testing equipment with the specific direction of rolling parallel or perpendicular to the loading, which typically yields a tensile failure. Accurately recording the thickness and diameter of the field core along with the ultimate load helps to compute the indirect tensile strength. This dedicated section compares the active resistance of field core specimens of both compaction methods. The field core thickness typically obtained from the trial site was in the range of 30-90mm. The trial mat was used for purposes like the determination of optimum rolling pass, thickness and temperature that created variation in mat thickness.

Later Figure 4-8 presents the average indirect tensile strength for both methods obtained by grouping field cores thickness.

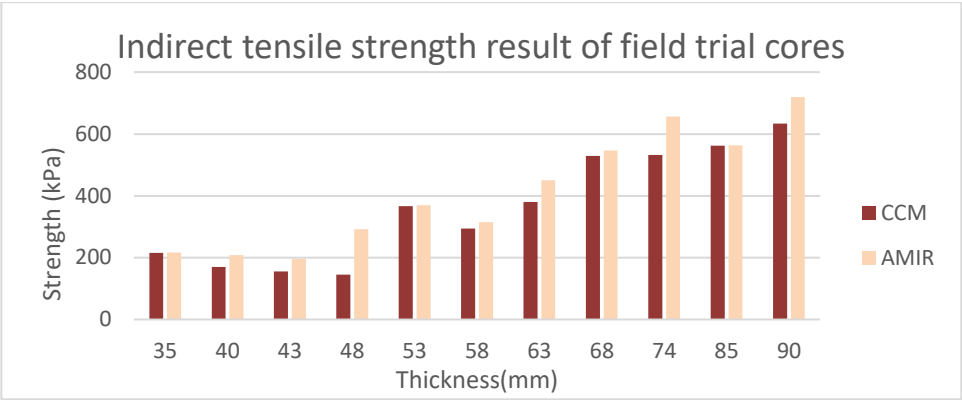


Figure 4-8 Indirect tensile strength result of field cores

The combined average strength of the CCM and the AMIR compacted field cores are 362.07 kPa and 412.24 kPa, respectively. The AMIR compacted field cores showed on average 0.88 times more resistance than the CCM, despite the CCM rollers combined rolling passes (17-22) being more than twice that of the AMIR roller (6-8). The result demonstrates that the circular and short duration contact of the CCM rollers on the asphalt mat produces lower strength than the flat and long duration contact provided by the AMIR method roller.

Figure 4-9 shows the exact measured thickness and the corresponding respective indirect tensile strength of the field cores. The test results shown in the figure are obtained by loading field core on the direction of rolling for both the compaction methods. The overall average thickness of the field cores from Figure 4-9 is 49.2mm

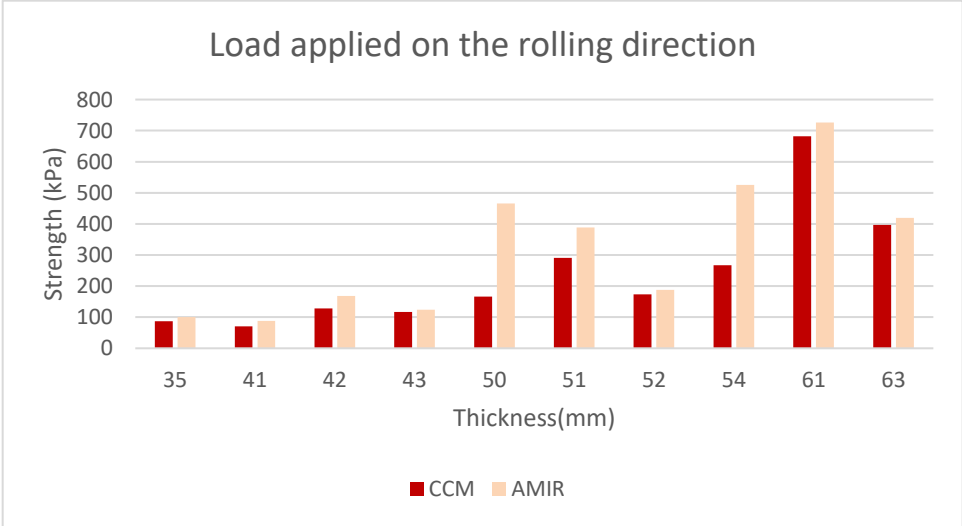


Figure 4-9 Indirect tensile strength by applying load on the direction of rolling

The combined average strength of the CCM and the AMIR are 238.06 kPa and 319.45 kPa, respectively. The previous result can be cautiously interpreted to mean that the AMIR compacted field core load in the direction of rolling produces 0.75 times more resistance than the CCM.

The subsequent Figure 4-10 shows the tensile strength of the field cores by loading perpendicularly to the rolling direction. The overall average thickness of the field cores from Figure 4-10 is 49.8mm. The combined average strength of the CCM and the AMIR

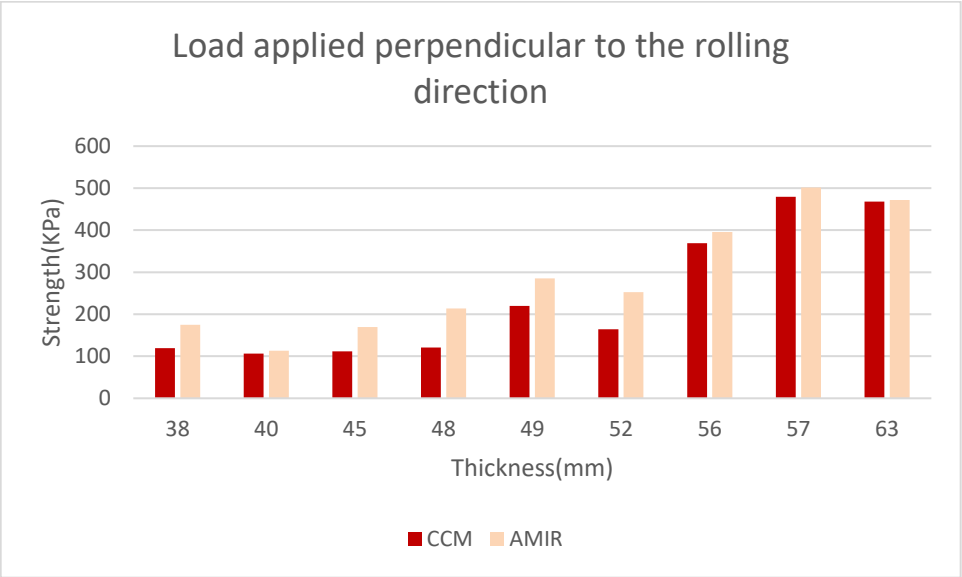


Figure 4-10 Indirect tensile strength by applying load perpendicular to rolling direction

are 239.76 kPa and 286.44 kPa, respectively. The above strength result can be interpreted as: the AMIR compacted field cores when loaded perpendicular to the rolling direction can resist on average a tensile force 0.84 times higher than CCM.

This section concludes that the AMIR technology can progressively improve a loose mat tensile strength by an average 0.88 times more than the CCM. As noted previously in chapter 2, the strength result ascertains that the concept of using a flat roller surface creates a more extended duration of contact with the asphalt mat, increasing the mat strength above that of the CCM rollers, which contact the mat in a circular (rolling) fashion for a limited duration. Moreover, the longer duration contact of the AMIR technology reduces the number of passes required to

increase mat strength compared to the combined rollers of the CCM.

4.5 Optimum requirements of the AMIR compaction technique

As noted previously, the acceptable limit of the percent compaction for a wide range of Superpave mixes is 92%. Several in-house trials were conducted in the Tomlinson Yard to determine the AMIR compaction optimum lift thickness, temperature, and passes necessary to meet the minimum percent compaction requirements for the MTO.

As shown in Photo 4-2, several in –house asphalt mats were laid and compacted using the

Photo 4-2 In-house trial for optimum rolling pass for AMIR

AMIR compaction method at different mat thickness, temperatures, and with varying numbers of rolling passes. The compacted mat cores were extracted for testing before the mat was opened to traffic to avoid compaction from vehicles. The extracted core thickness and percent compacted density was checked at the Carleton Civil Engineering Laboratory. To avoid personal bias and to confirm the accuracy of testing, the compacted cores of the in-house trials were crosschecked by a Canadian Council of Independent Laboratory (CCIL) certified Laboratory, located in Ottawa, Canada and the results are produced in Tables 4-7 to 4-9.

Table 4-7 AMIR compacted mat at 90°

Thickness (mm)	Pass	BRD	MRD	% compaction
78	2	2.317	2.477	93.5
63	2	2.319	2.469	93.9
64	4	2.315	2.478	93.4
58	4	2.318	2.487	93.2
70	6	2.326	2.475	94.0
74	6	2.338	2.481	94.2

Table 4-8 AMIR compacted mat at 105°C

Thickness (mm)	Pass	BRD	MRD	% compaction
110	2	2.275	2.469	92.1
80	2	2.271	2.472	91.9
100	4	2.302	2.472	93.1
78	4	2.329	2.485	93.7
80	6	2.298	2.481	92.6
75	6	2.333	2.502	93.2

Table 4-9 AMIR compacted mat at 115°C

Thickness (mm)	Pass	BRD	MRD	% compaction
88	2	2.308	2.478	93.1
78	2	2.295	2.483	92.4
98	4	2.320	2.473	93.8
85	4	2.320	2.477	93.7
67	6	2.330	2.481	93.9
61	6	2.344	2.487	94.3

It is evident from the above tables and subsequent figures 4-11 to 4-14 given below that the AMIR compaction technology has a capability to compact asphalt mat average thickness of

70mm at the temperature of 90°C within two passes without vibration. This meets the MTO's acceptable percent compaction density that was specified previously in Table 4-1.

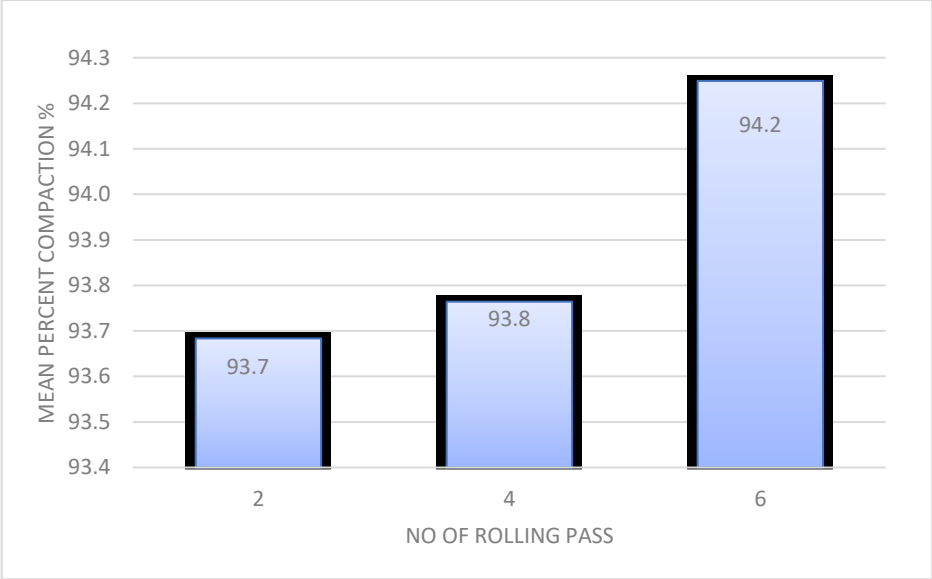


Figure 4-11 AMIR compaction method optimum rolling pass at 90°C

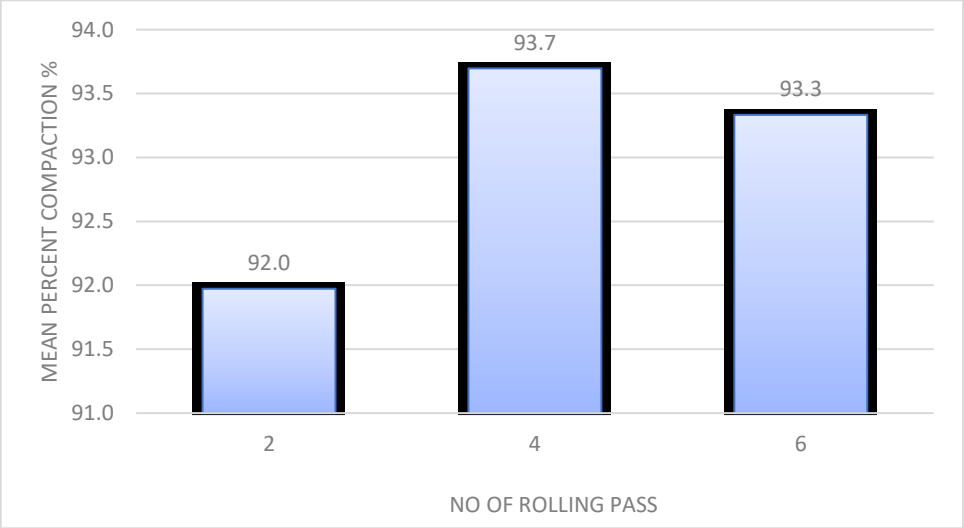


Figure 4-12 AMIR compaction method optimum rolling pass at 105°

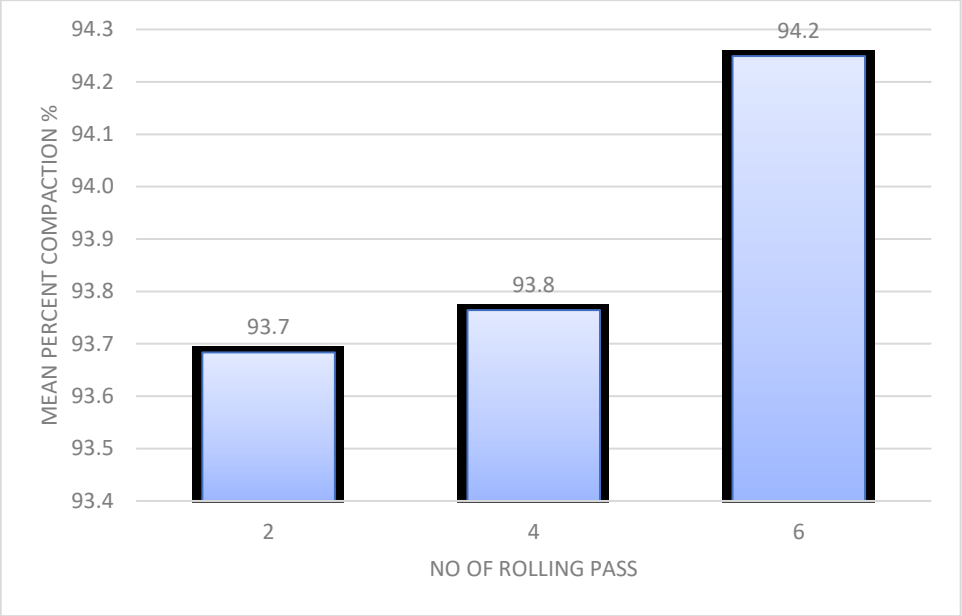


Figure 4-13 AMIR compaction method optimum rolling pass at 115°C

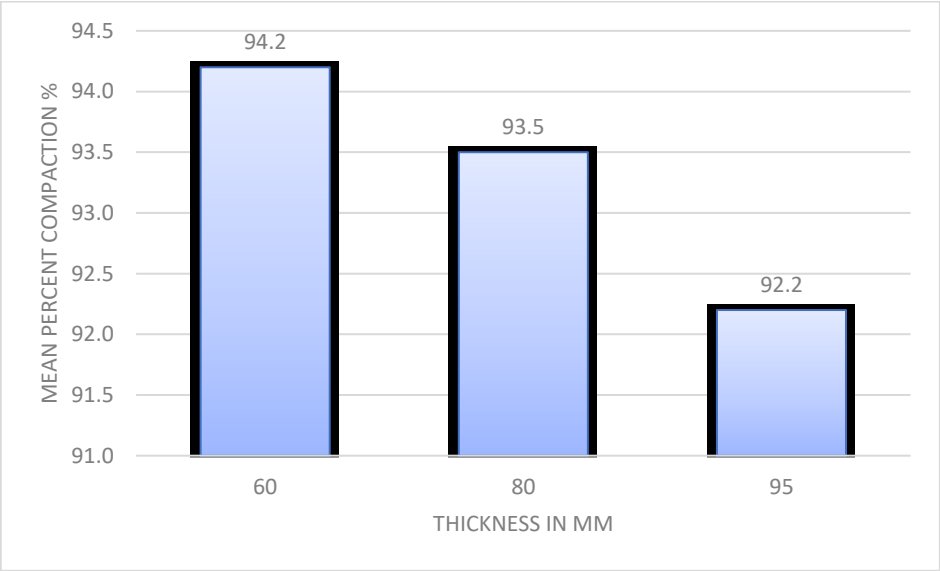


Figure 4-14 Optimum lift thickness of AMIR compaction method

In summary, the in-house trials displayed that the AMIR technology has an ability to compact a thicker mat at a lower compaction temperature and with a minimal number of passes. The in-house trial findings were crossed checked and confirmed by a CCIL certified laboratory to avoid bias and to verify the accuracy of testing that had been undertaken at the Carleton University Civil Engineering Laboratory.

4.6 Evaluation of long-term performance

This specific section presents the long-term performance of the compacted asphalt mat using the CCM and the AMIR technologies. Previous compaction studies of the AMIR roller stopped at field and laboratory studies. This is the first study to thoroughly research the performance of the AMIR compacted asphalt mat in direct comparison with the CCM is sufficiently studied. The review process and the cause for reduced performance of trial sites were standardized by following the Manual for Condition Rating for Flexible Pavements SP024 (Ministry of Transportation Ontario, 1989).

Only provincial highway trials referred to as "common" in this study are considered for the performance review due to consistency in laying procedure, testing method and traffic volume. A successful trial is referred to as "common" when the paving process carried out by laying sections of the CCM and the AMIR side by side. Between the summer of 2012 and fall 2015, a total of eight common trials were conducted using CCM and AMIR technologies.

Six out of eight trials are provincial highways, and the remaining two are in-house trials. The trial pavement sections of the HWY 7 were removed from the long-term performance review due to mix design nonconformance. Out of five remaining provincial highway trials, one highway (HWY 34) trial was paved separately as a result of construction staging. The CCM section was laid a month earlier under a warm weather condition (air temperature 20°C and above). The AMIR section was paved under colder weather conditions (air temperature -1°C to -3°C). Later Table 4-10 presents the trial locations that are considered appropriate for the yearly performance review.

\

Table 4-10 Trial locations for long-term performance review

Location	Trial date	Final Review date	Base type	Weather	Lift thickness (mm)	
					CCM	AMIR
HWY 28	September 13,2012	June 26,2018	Granular	Sunny warm	1 lift 50	1 lift 50
HWY 2 S	July 24,2012	June 19,2018	Granular	Sunny warm	1 lift 50	1 lift 50
HWY 34	November 27,2014	July 4,2018	Concrete	Sunny cold	2 lifts 50-40	1 lift 90
HWY 401	September 18,2015	July 12,2018	Concrete	Sunny warm	2 lifts 50-40	2 lifts 50-40
HWY 520	December 01,2015	August 16,2018	Concrete	Sunny Cold	2 lifts 50-40	2 lifts 50-40

This study looked at typical defects, including surface deformations, surface defects and cracks.

Surface Deformations

- Rippling and Shoving
- Wheel Track Rutting
- Distortion

The trial locations had no surface deformations.

Surface Defects

- Flushing
- Ravelling

The trial locations were free from flushing defects.

Figure 4-15 shows a sample sketch of performance review. The subsequent Table 4-11 reflects the average ravelling from each trial section for both the compaction methods. The AMIR section had slight few ravelling at the HWY 28 and the HWY 2 S locations.

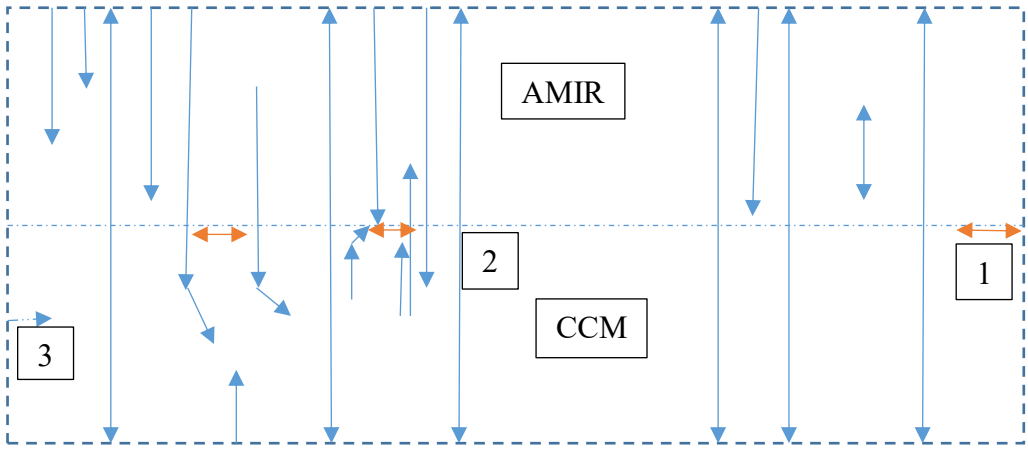


Figure 4-15 HWY 2 S sample sketch of surface condition (performance year six)

where;

1 denotes = centerline crack

2 denotes = transverse crack

3 denotes = longitudinal crack

The cause of the raveling in the AMIR section is due to the use of a petroleum product as the release agent to avoid having asphalt stick to the roller. The AMIR sticking issue was resolved by replacing the rubber roller belt to Teflon along with a release agent made from a blend of canola-based synthetic lubricants. Highways HWY 34 and HWY 520 had a very slight few raveling in the AMIR trial locations. The paving trial was performed at both locations when the ambient air temperature was below -1°C. Despite these unfavorable paving conditions, the AMIR compacted sections displayed superior resistance to surface defects compared to the CCM. According to SP024, raveling may be due to poor compaction of asphalt mat or poor adhesion asphalt material on aggregates. If the reason is poor adhesion, both the CCM and AMIR mats should have close to the similar amount of raveling. As the AMIR compacted mat possessed lower average raveling in most of the trial sites when compared to the CCM, it can be concluded that poor compaction of the asphalt may be the reason for the raveling in the CCM section.

Photo 4-3 HWY 34 CCM section with ravelling performance year four

Photo 4-4 HWY 2 S AMIR section with raveling performance year six

Table 4-11 Surface defects-raveling in the trial locations

Location	CCM	AMIR
HWY 28	Slight Few	Slight Few
HWY 2 S	Very slight Frequent	Very slight Few
HWY 34	Slight intermittent	Very Slight Few
HWY 401	Slight Few	Very slight Few
HWY 520	Slight Few	Very slight Few

Cracking

- Centerline: Single and Multiple
- Longitudinal Wheel Track: Single and Multiple
- Pavement Edge: Single and Multiple
- Transverse: Single and Multiple
- Longitudinal: Meander or Mid-lane

Possible cause for surface defects:

Table 4-12 below compares the combined surface crack defects of individual trial locations compacted by CCM and AMIR rollers. The SP024 (Ministry of Transportation Ontario, 1989) suggests that longitudinal wheel truck cracks and longitudinal mid-lane cracks may be due to fatigue and a weak plane. In the compacted sections of HWY 28, HWY 2 S and HWY 34, slight few longitudinal cracks were visible in the CCM as shown in photo 4-5. The AMIR compacted sections had no visible cracks. The reason for cracks in the CCM may be due to a weak plane resulting from poor compaction.

Photo 4-5 HWY 28 CCM section with longitudinal crack performance year six

The AMIR roller compacted most of the centerline joint. One of the fundamental deficiencies of the CCM is that it is not able to compact the unsupported edge because of problems in the roller design as explained earlier in Chapter 2. For the purposes of this study, a visible crack is

considered being a centerline crack when it is away from the wheel path close to the centerline or on the joint. The SP024 cautions that the centerline cracks may be due to poor joint construction practices.

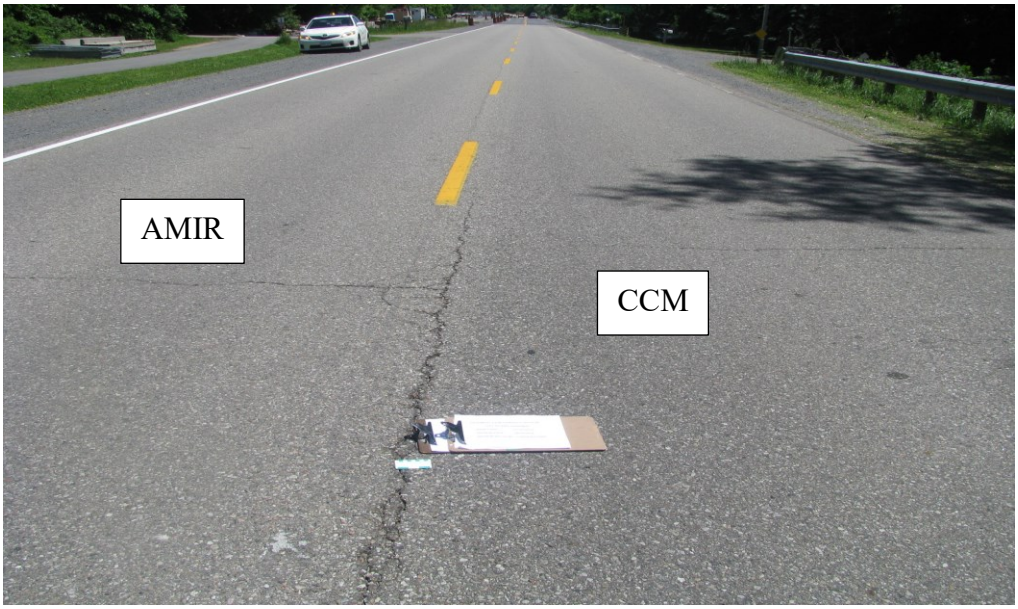


Photo 4-6 HWY 2 S CCM section with centerline crack performance year six

A centerline joint crack was noticeable in all the CCM trial sections as shown in photo 4-6, with the exception of HWY 401. On the other hand, the AMIR compacted trial sections had no centerline or longitudinal cracks, except for at the HWY 28 site. It can be concluded that poor joint compaction practices may be the reason for the longitudinal crack close to the centerline in the CCM section.

Pavement edge cracks were visible in both the CCM and AMIR sections in the trial locations at HWY 28, HWY 2 S and HWY 34. The SP024 suggests that insufficient bearing support may be a possible cause of edge cracks. The trial locations of HWY 2 S and HWY 34 had slight extensive transverse cracks that ran the full width of the trial section as shown in succeeding photo 4-7. The specific cause of transverse cracks in the trial locations was not apparent. According to the SP024, this may be due to shrinkage, frost action or the low-temperature susceptibility of asphalt cement in asphalt mixes.

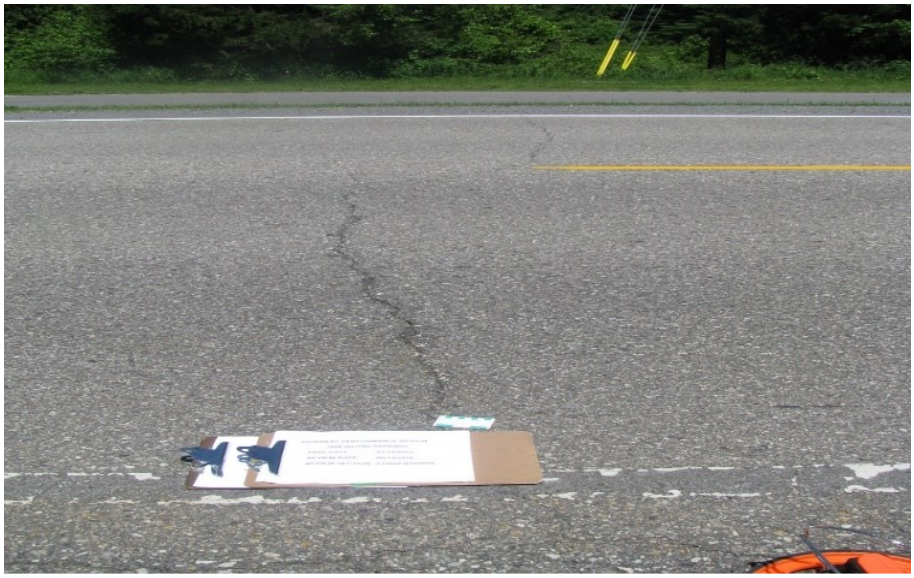


Photo 4-7 HWY 2 S transverse crack running full width performance year six

Tables 4-12 and 4-13 compare the combined surface crack defects of individual trial locations compacted by CCM and AMIR rollers. Observation from the tables reveals that the AMIR compacted section deterioration rate is much slower than CCM.

Table 4-12 Comparison of Provincial highways surface crack in granular base

Crack type	**HWY 28**		**HWY 2 S**	
	CCM	**AMIR**	**CCM**	**AMIR**
Longitudinal wheel truck	Slight frequent	None	None	None
Centerline	Slight frequent	Very slight few	Slight intermittent	None
Pavement edge	Slight extensive	Slight extensive	Slight frequent	Slight frequent
Transverse	None	None	Slight extensive	Slight extensive
Longitudinal mid-lane	Slight frequent	None	Slight few	None

Table 4-13 Comparison of Provincial highways surface crack in granular base

Crack type	HWY 34		HWY 401		HWY 520	
	CCM	**AMIR**	**CCM**	**AMIR**	**CCM**	**AMIR**
Longitudinal wheel truck	None	None	None	None	None	None
Centerline	Slight frequent	None	None	None	Slight intermittent	None
Pavement edge	Slight intermittent	Slight few	None	None	None	None
Transverse	Slight extensive	Slight extensive	None	None	None	None
Longitudinal mid-lane	Slight few	None	None	None	None	None

Summary:

Field performance review observation suggested that AMIR compacted pavements will require less maintenance due to better performance compared with the roads finished by CCM. Presence of centerline crack, edge cracks and surface cracks become potholes in the CCM compacted surfaces and few or absence in the AMIR compacted surfaces along with the higher deterioration rate of CCM when compared with the AMIR compacted sections supports the theory of CCM design issues that had been identified by Abd El Halim et al. (1985, 2006, 2016).

Chapter 5 : Regression model and Economic analysis

5.1 Mathematical model for Compaction

This devoted chapter comprises of two sections. The first section explains the influence of compaction method on performance of compacted mat and permeability using a mathematical model. The final sections describe the variance between the compaction methods of CCM and AMIR through economic benefits, which was obtained as a result of an economic analysis of compaction method in terms of equipment, manpower, and time.

For more than half a century the pavement researchers and managers focused on developing long-term performance models to predict when corrective actions and proper treatments can be considered. However, most developed asphalt pavement predictive models by assuming that the finished asphalt pavements are free of defects and that any deterioration is due to the combined actions of climate and traffic. This thesis identifies two compaction technologies and for the first time provides an opportunity to examine the effect of different compaction technologies on the long-term performance of different asphalt roads paved with various types of mixes as explained earlier in the thesis.

Of course, the absence of a different compaction method than the CCM prevented the consideration of the influence of compaction type and subsequently the initial condition of the finished pavement. As a result of this shortcoming, most research carried out on the subject failed to provide any reliable prediction of pavement performance. A research by Nordic countries observed that "Although much research has been devoted to performance modelling of pavements, a comprehensive model that can predict pavement performance accurately has yet to be developed". It was concluded that there is a need to develop improved models for use both at the network level and the project level [Nordic]. In this section, a new attempt is made to develop a model which considers variables related to the initial conditions of the finished pavement such

as the type of compaction, number of passes, surface conditions of finished pavement permeability and percentage of compaction among other variables. The model is split into two sub-models; one based on asphalt compacted with CCM rollers and the other one is finished using AMIR compactor. The regression prediction model is developed in order to understand the impact of compaction methods on asphalt pavement performance and permeability. The dependent variable is *damage index* (DI) at service time of compaction (0), and in subsequent years. In this thesis, the number of years considered is three. In this thesis, seven independent variables and four different time periods were considered for DI model development. Data for the model were collected from field and laboratory tests. The compaction method's influence on pavement distress and permeability are presented in this section. The conclusion arrived with multiple pieces of evidence of significant results in the model, by using choice of predictors, goodness- of- fit and associations between predicted and observed data.

5.1.1 Data

Over the course of this five-year study, annual performance review was conducted for the HWY trial sites at 2 S, 7, 28, 34, 401, 520, Didsbury road and in-house. The standalone trial location where a single compaction method was used are at HWYs 16, 17, and 417 which are considered as missing data. Trial location HWY 7 performance review was stopped at year 2 due to the removal of trial site by the owner for segregation reason. Trial locations Local road (Didsbury) and Tomlinson yard 2016 PCI reviews stopped at year one and two as the pavement has not reached the service year during the time of writing. The missing years of service life for the CCM sections at Local road, Tomlinson yard and HWY 7 were obtained by linear interpolation and for the AMIR sections at the same location by series mean. The method chosen for the replacing of missing values was based on the collected data. The above process generated 180 field points suitable for analysis. The data used for various models are categorized by pavement base and

roller type as shown in the Table 5-1.

Table 5-1 Data

Base type	CCM rollers	AMIR roller	Total
Granular base	55	80	135
Concrete base	21	24	45

The independent variables that are considered for the regression prediction model is given in the below Table 5-2.

Table 5-2 Independent variable considered for regression analysis

Category	Variable	Measurement type
During Compaction	Number of passes (*NP*) -- *IV*	Field value
	Thickness of asphalt mat (*T*)--*IV*	
	Permeability (*Perm*)--IV	
	Pavement type (*Pavt)*-----IV Dummy variable	0-Concrete base overlay 1- Granular base overlay
	Roller type (*Rol*)----------IV Dummy variable	0-AMIR; 1- CCM
Laboratory	Percentage of compaction of field core (*Comp*)---------- IV Indirect tensile strength (*IDS*)--IV	Laboratory measured value
Performance review		
At zero year	Damage index *(DI_0*) -------IV/DV	Field value
After one year	Damage Index (*DI_ 1)* ---IV/DV	
After two year	Damage Index (*DI_2)* ---IV/DV	
After 3 year (DV)	Damage Index (*D*I_*3*--- DV	

The long-term performance of compacted asphalt pavement for both methods was determined by pavement damage index (DI) by slightly modifying the procedure of the pavement condition index guideline of MTO (Ministry of Transportation Ontario, 1989). Road authority like MTO use pavement condition index (PCI) a surface condition survey objective tool to justify their

rehabilitation work (Ministry of Transportation Ontario, 1989). The PCI yield numerical values in percentage for the reviewed section of road from the measures of severity (type) and density (occurrence) of pavement surface distress like crack, distortion, based on field observation and riding condition of the surface ((MTO, 1989), (Ningyuan, Kazmierowski, & Koo, 2011)). In this study, to get a numerical value the *DI* was calculated by combining the number of distress severity and density and then multiplied by its weight factor for each year that the pavement was in-service for the study period. Riding condition was eliminated to reduce the bias. The weight factor, a number to represent the pavement surface condition for severity and density assumed in the range from 0.5 to 4 in this thesis following the range used by Ningyuan et al., (2011). Road authorities modify the weight factor regularly based on the condition of road network (Ningyuan, Kazmierowski, & Koo, 2011)

$$\mathrm{DI} = W(S + D) \qquad (5\text{-}1)$$

Where,

W = weighted factor between of 0.5 to 4 represents the weighted feature of individual pavement surface condition of a trial section under as listed in appendix 3.

S = Severity in the scale 1-5 with a range of 0.5 to 4.

D = Density in the scale 1-5 with the range of 0.5 to 4

DI= Damage index in percentage

Procedure for pavement condition surface review:

1) Divide the trial section into sections.

2) Observe and record the distress.

3) The final DI is the measured pavement surface distress number obtained by the sum of individual DI of the trial section for the observed year. A sample work sheet is shown in Table 5-3.

Table 5-3 Sample DI work sheet

Pavement Crack type	Range	Severity of Distress (S)					Density of Distress (D) in estimated percentage				
		0.5	1	2	3	4	.5	1	2	3	4
		Very slight	Slight	Moderate	Severe	Very Severe	Few	intermittent	Frequent	Extensive	Throughout
							<10	10-20	20-40	40-80	>80
	Scale	1	2	3	4	5	1	2	3	4	5
	Wi										
Construction	4										
reveling	3										
Longitudinal wheel track	1.5										
Centerline	0.5										
Transverse	1.0										
Longitudinal midlane	1.0										
Pavement Edge	0.5										

Construction cracks or check cracks are formed during construction while using compaction equipment. During field observation, construction cracks were found as short transverse cracks, usually after the first or second pass of the compaction equipment over the mix. The cracks range from 25mm to 100 mm in length and 24 to 60mm apart. The construction cracks are neglected by the road authorities around the world considering them to be powerless. Research work of Abd El Halim et al. (1985, 2006, 2013) has considered construction crack is one of the causes for early surface deterioration and acts as a booster for several surface cracks like longitudinal, transfers cracks that would eventually lead to a pothole in the asphalt pavement. For the first time, construction cracks are captured and estimated in the weight of 4, severity and density scale of 1-5 and range of .5 to 4. The weight of 4 was assumed based on the engineering decision of

considering the construction cracks to have a major impact than the ravel on the asphalt mat after reviewing several works of Abd El Halim et al. (1985, 2006, 2013)

The yearly performance review of field trial sites ranges from one year to a maximum of six years. The DI of the trial pavement was calculated and grouped according to the compaction method and into four service year groups during construction year 0, at service year 1, service year 2, and year 3 above considered as service year 3. Pavement condition review for damage is considered as year zero (*D1_0*) when the surface review was made on a fresh asphalt mat right at construction start of service life (i.e. before open to the public traffic). The first-year review of pavement was conducted after open to public for service is *DI_1*, similarly *DI_2* and *DI_3* if the pavement surface review was conducted on the second and third or more years of service life. *DI_0*, *DI_1*, *DI_2*, considered as independent as well as dependent variables and *DI_3* only as a dependent variable.

5.1.2 Ordinary least squares regression model:

Modelling procedure

A general (g) model with four statistical models, two roller specific models (CCM, AMIR) with four statistical models each is developed to predict the field damage index of asphalt pavement for four service years. The dependent variable used in each of the following statistical analysis is the pavement damage index (DI), which provides a measure of the level of road deterioration and the damage incurred on the road. Multiple regression procedure is used in this analysis, which specifies the dependent variable to be a linear function of the independent variables, along with many assumptions on the random error term. These assumptions include a normal distribution of the error term, zero mean, constant variance for all values of the independent variables, independence of the error terms for each observation, and the correct specification of the variables.

A multiple linear regression model form is given below (Field, A,2012):

$Y = \beta 0 + \beta 1*X1 + \beta 2*X2 + ... + \beta k*Xk + \varepsilon$

where X1, ..., Xk are the independent variables

$\beta 0, ..., \beta k$ are the parameters of interest

ε is the error term that is assumed to have a normal distribution with mean '0' and constant variance (homoscedasticity assumption).

The following procedure applied to predict pavement damage index for four time periods from the year 0, 1, 2 and 3or more for asphalt pavement:

(1) The generic model created using 180 final data points.

(2) The roller specific models of the AMIR and CCM were created using their respective data points of 104 and 76.

(3) The multiple regression analyses carried out by the ordinary least square procedure in SPSS ® version 22 in the Windows 10 environment.

(4) The choice of the independent variables has been completed using a stepwise and forced entry regression procedure. The stepwise procedure includes building a forward model from the no-variable model, and then checks iteratively whether previously added variables can be dropped from the models, after including the latest variable (Field, A, 2012). The variables that are dropped out or kept in by the stepwise procedure were forced out or placed in to find the most significant variables.

(5) Overall statistical significance of the model verified using the ANOVA-F test, which is then followed by the significance of the independent variables in the model, and then completed by the checking of the correct signs on the independent variables.

(6) The model assumptions are checked before using a measure of model prediction (adjusted R-squared). These steps are followed in a consistent manner in this regression modelling, whose results are provided in the following sections.

Variables that are considered for the modelling and its description shown in the Table 5-4
.

Table 5-4 Variables considered for predicting damage index

Variable		**AMIR method** **Roller I**	**CCM method**		
			Rollers I (with vibration)	**Rollers II (with pneumatic)**	**Rollers III (without vibration)**
During Compaction	NP	2 to 8	8 to 12	13--21	2-3
	T mm	40-95	38-85		
	Perm cm/sec	.0000105-0.02530	.0000204 -.0453000		
	Comp %	86-98	86-94		
	Pavt	Dichotomized variable 0-Concrete base overlay; 1- Granular base overlay			
	Rol	Dichotomized variable 0-AMIR; 1- CCM			
Laboratory	IDS kPa	75-1024	61-697		
Performance review					
	Construction crack	0	10cm		
	Ravel	0-12m	0-12m		
	Centerline crack	0-3m	0-11m		
	Pavement edge	0-50m	0-50m		
	Longitudinal crack	0	0-2m		
	Transverse crack	0-6m	0-6m		
	Mid lane crack	0	0-4m		
At zero year	DI_0 in %	0-0	4-20		
After one year	DI_ 1 in %	0-3	4-30		
After two year	DI_2 in %	0-7	4-45.50		
After 3 year (DV)	DI_3 in %	0-16	4-46.25		

(7) The independent variables have been chosen on the basis of a good blend of theory and

statistical procedures. As mentioned earlier, Stepwise regression and forced entry procedures have been employed for the models in order to identify the most significant variables needed to explain the DI for each of the time periods.

(8) The test of homoscedasticity (constant variance) is done using a special package on the SPSS, which was developed by Hayes, A.F., & Cai, L (2007). The resulting Breusch-Pagan estimates have been used in the estimation of standard error for the regression estimates and to adjust for the non-constant variances. In the succeeding tables 5-8 to 5-11, 5-14 to 5-17 and 5-20 to 5-21 for estimated coefficients of the different models, the 'adjusted standard error' refers to the heteroscedasticity corrected estimates.

5.1.3 Regression model functional form

There are three broad categories of models that have been employed in this analysis, which includes the basic or general model, CCM specific model, and the AMIR specific model. Time zero is during the construction of asphalt mat is included in the model to see the effect of independent variables like pavement type, roller type, thickness, roller passes, % compaction achieved on the field core, permeability, IDS on the long-term performance of the asphalt mat. For the general and CCM models, all four time periods from year 0, 1, 2 and 3, have been modelled since each of the time periods have produced models in terms of the independent variables. For AMIR specific model, time period 0 has been excluded since it did not provide a significant regression model as there were no construction cracks during construction.

The functional form along with the final set of independent variables chosen for each model category and time period is given below.

General model:

DI_0(g) = f (Rol, Pavt, T, NP)

DI_1(g) = f (DI_0, Rol)

DI_2(g) = f (DI_1, Rol, T)

DI_3(g) = f (DI_2)

CCM specific model:

DI_0(CCM) = f (Pavt, T, NP, T*NP)

DI_1(CCM) = f (DI_0)

DI_2(CCM) = f (DI_1, Pavt, Perm)

DI_3(CCM) = f (DI_2)

AMIR specific model:

DI_0(AMIR) = 0

DI_1(AMIR) = f (NP, Comp, NP*Comp)

DI_2(AMIR) = f (DI_1, Pavt)

DI_3(AMIR) = f (DI_2)

From the models that have been estimated above, several interesting results and trends can be observed, which provide more insight into understanding the dependent variable, *DI*. The general expectation of the signs for independent variables in any of the time periods can be stated in advance with the help of literature view of past research work that has been outlined in Chapter 2 of this thesis. The variables such as *percent compaction of a field core (Comp)*, the number of *passes by roller (Passes)*, and *thickness* of *asphalt mat (T)* at pavement design level tend to have a negative linear relationship with *DI* (Epps et al. (1969,1980), Kennedy et al. (1984) and Fisher et al. (2010)).This is because *DI* increases when the quality of the road and the many individual determinants of its structural and functional integrity go down.

On the other hand, lower compaction increases roller passes, and mat thickness creates negative linear relationships with *DI* if their values wouldn't meet the design level. This will cause the integrity of the road segments to go down, which makes them more prevalent to deterioration

and damage. The negative effect of higher mat thickness depends on the type of roller. Field Observations of in-house and HWY 34 trials showed thicker asphalt layer reduces construction joints like centerline and transverse. In turn reduce the DI values. The CCM roller circular shape and the choice of hard steel material which is a design flaw generate intense pressure impulse to compact increased layer thickness. The increased impulse causes construction cracks, poor compaction at joints and loose surface texture lead to an increase in damage index.

On the other hand, AMIR roller flat and flexible contact area provides asphalt surface layer does not crack during compaction with the tighter texture. HWY 34 and in-house trials of the AMIR roller demonstrated the roller can compact a lift thickness of 100 mm to required designed compaction level. The maximum lift thickness allowed for the CCM roller by the road authorities during the trial was 50mm.

When the number of passes made is increased in an asphalt mat, the road is solidified to the design requirement, but this also depends on the type of roller since the CCM roller behaves differently and provides different results than the AMIR roller. The design flaws of the CCM roller create construction cracks during the construction stage. The presence of construction cracks on the pavement surface could lead to other cracks such as thermal, reflection and ultimately to potholes Abd El Halim et al. (2006, 2013, 2016). When the mentioned cracks happen, the incidence of DI also goes up.

Other variables such as water permeability and pavement type would have a positive relationship with the dependent variable. In the case of water permeability, if the permeability value of the pavement increases, then the structural integrity of the pavement goes down because of water and air movement. Moisture and air may enter through poorly compacted asphalt mixture under favorable condition are capable of stripping the bond between asphalt binder and aggregate. The losing the bond often accelerates pavement deterioration. Asphalt surface that allows water

increases the potential of air. Oxygen in the air reacts with an asphalt surface over a period could cause the asphalt pavement to fail by making the asphalt too brittle, reducing load carrying capacity, resulting in fatigue and cracking. Therefore, when the permeability of the asphalt surface increases, the incidence of DI also goes up, which should happen for both the roller types Abd El Halim et al. (2006,2013. 2016).

The variable pavement type dictates the choice of construction, staging and equipment selection. For example, concrete bridge deck asphalt overlay pavement does not allow the use of the CCM method's vibratory roller (Ministry of Transportation, 2015). Poor construction stage, equipment and pavement choices could lead to poor compaction. The CCM roller's design flaws create construction cracks during the first period itself (year 0), which lends itself to more maintenance and other structural issues when compared to the AMIR roller in general. The results of the estimated models are all provided in the following section which provides the values of the various coefficients and summary measures for the regression.

5.1.4 General model:

General model ANOVA estimate:

Table 5-5 ANOVA estimates for general model

General Model	F	Sig
DI_0g	616.95	.00
DI_1g	1054.27	.00
DI_2g	2470.25	.00
DI_3g	484.238	.00

The above Table 5-5 provided to show the significance of the model fit. Higher F values of the individual model suggest respective model variables possess the significant capability to predict their respective *DV*s $DI\_0_{(g)}$, $DI\_1_{(g)}$, $DI\_2_{(g)}$, *and* $DI\_3_{(g)}$. Therefore, a null hypothesis of the insignificance of the overall model can be rejected.

General model performance measure

The following Table 5-6 provides measures of model fit and prediction values in the form of adjusted R square for the general model for various time periods. The multiple correlation coefficient, R, is a measure of the correlation between the independent variables mentioned in the functional form of general model equations with their respective $DI\_0_{(g)}$, $DI\_1_{(g)}$, $DI\_2_{(g)}$, *and* $DI\_3_{(g)}$(dependent variable) which could be obtained by taking the square root of individual adjusted R square value.

The coefficient of determination for the combined independent variables and the dependent variable denoted by adjusted R^2 with the respective values of 0.93, 0.92, 0.98 and 0.92 which implies that 93%,92%, 98%, and 92% of the variation of respective $DI\_0_{(g)}$, $DI\_1_{(g)}$, $DI\_2_{(g)}$, *and* $DI\_3_{(g)}$ could be explained by their respective combined independent variables. The adjusted R^2 accounts for some of the error associated with the model for various independent variables. Finally, a standard error for the estimate that indicates that $DI\_0_{(g)}$, $DI\_1_{(g)}$, $DI\_2_{(g)}$, and $DI\_3_{(g)}$ estimated by their individual models and will deviate from the true value by 2.23, 2.28, 2.10, and 4.10.

Table 5-6 Summary of model performance measures for general model

General Model	Adjusted R2	Standard Error of the estimate
DI_0g	.93	2.23
DI_1g	.92	2.88
DI_2g	.98	2.10
DI_3g	.92	4.10

The heteroscedasticity (non-constant variance) in terms of model residual standard error was adjusted by following the procedure outlined by Hayes, A.F., & Cai, L. This is done to provide a reliable model coefficient values and not to be deceived by high R^2 values as shown in earlier

the Table 5-6.

Tables 5-7 to 5-10 provides regression results with estimated coefficients (B), standard error, t-statistics, and p-values with and without heteroscedasticity adjustment for standard errors. The regression coefficient of individual independent variables "t" value reveals that the partial slope of each independent variable (after holding other independent variables constant) is significantly different from zero.

The p values associated with each independent variable are much smaller than 0.05 showing that each of the model's independent variables is a significant predictor of pavement damage index (*DI)* Tables 5-7 to 5-10 shows that heteroscedasticity adjustment for standard error has no impact on the model B values, but influence can be seen in standard error, t and p values. The adjusted tables 5-7 to 5-10, values for independent variables are reliable statistically as significant predictors on their respective DVs $DI\_0_{(g)}$, $DI\_1_{(g)}$, $D1\_2_{(g)}$ and $DI\_3_{(g)}$.

General model regression equation

The equation for predicting pavement damage index at time 0 is created by utilizing the succeeding Table 5-7 regression coefficient values (B). The equation for DI_0 is given below

DI_0 (g) = -8.219+(19.932*Rol) +(3.721*Pavt) +(1.183*T) + (-0.269*NP) *-------(*5-1)

Table 5-7 Estimated regression coefficients for general model D_0(g)

Variable	B	Standard error		t		sig	
		Real	Adjusted	Real	Adjusted	Real	Adjusted
Constant	-8.22	1.60	1.79	-5.14	-4.60	.00	.00
Rol	19.93	.66	.60	30.22	33.48	00	00
Pavt	3.72	.64	.73	5.81	5.10	00	00
T	1.18	.18	.18	6.72	6.45	00	00
NP	-0.27	.05	.06	-5.50	-4.45	00	00

The following is the interpretation of unstandardized regression coefficients, which is the relationship between various independent variables with dependent variable (DI_0g) when

controlling for the other independent variables. Equation 5-1 suggests that for every additional unit increase in each of Rol, Pavt and T, there is a corresponding predicted increase of 19.932 units, 3.721 units and 1.183 units of the dependent variable, damage index at time o, respectively. On the other hand, for every additional unit increase in construction crack free NP, there is a corresponding predicted decrease of 0.269 units in damage index at time 0. If increased layer thickness is compacted to the required design level, then the benefit of reducing construction joints (transfers and horizontal) and increasing the strength of the asphalt mat could be obtained. If the unit increase in layer thickness is not compacted properly, this this will increase damage index in year 0 by 1.183 units.

Equation for predicting pavement damage index (DI) of asphalt mat at year 1 for general model using succeeding Table 5-8 regression coefficient values (B) is given below:

D_1 (g) = -1.106 +(.775* D_0) + (6.832*Rol) ----------(5-2)

Table 5-8 Estimated regression coefficients for general model D_1(g)

Variable	B	Standard error		t		sig	
		Real	Adjusted	Real	Adjusted	Real	Adjusted
Constant	1.11	.28	.10	3.91	10.97	.00	.00
DI_0	.78	.08	.12	9.98	6.63	.00	.00
Rol	6.83	1.34	2.02	5.10	3.39	.00	.00

The regression equation 5-2 is interpreted as follows: when controlling for the other independent variables, for every additional unit increase in damage index at time 0 and Rol there is a corresponding predicted increase of .775 units and 6.832 units in damage index at year 1, respectively. In other words when other variables are controlled, a unit increase of damage index in year 0 will increase damage index at year 1 by.775 units. The construction cracks caused by utilizing CCM roller in construction stage will increase damage index in year one by 5.726

(=6.832-1.106) units. Construction cracks are not created by the AMIR roller due to the more appropriate and superior design. Therefore, there is no impact.

Regression equation for general model at year 2 utilizing regression coefficient values of later Table 5-9 is given below

DI_2 (g) = 7.76 + (1.63 *D_1) + (-7.12*Rol) +(-.81*T) ----------(5-3)

Table 5-9 Estimated regression coefficients for general model D_2 (g)

Variable	B	Standard error		t		sig	
		Real	Adjusted	Real	Adjusted	Real	Adjusted
Constant	7.76	.68	.60	11.41	12.95	.000	.000
DI_1	1.63	.05	.06	35.41	26.20	.000	.000
Rol	-7.12	.96	1.10	-7.43	-6.50	.000	.000
T	-.81	.11	.10	-7.36	-8.07	.000	.000

The regression equation DI_2g is interpreted as when controlling for the other independent variables, for every additional unit increase in damage index at year 1 there is a corresponding predicted increase of 1.628 units in damage index at year 2. On the other hand, for every additional unit increase in Rol and T there is a corresponding decrease of 7.122 units and 0.809 units in damage index at year 2.

When controlling for other variables, a unit increase of damage index in year 1 will increase damage index at year 2 by 9.39 (7.76+1.63) units. On the other hand, when CCM roller is utilized for compaction at time 0, the construction cracks produced by the CCM roller at time 0 is increased by one unit then this effect will increase damage index in year two by 0.64 (=-7.12+7.76) units. AMIR roller doesn't produce construction cracks. Therefore, it has no impact. Increasing layer thickness in the form of crack sealant or micro surfacing by one unit in year 2 will reduce the damage index at year 2 by.809 units. The sealing of cracks was not done to the full extent of the trial section, and this was noticed during the field review for damage index.

The model equation correctly predicted the observation by showing an increase in damage index at year 2 by 6.95 (=7.76-.81) units despite the preventive maintenance.

The equation for general model damage index for year 3 using following Table 5-10 regression coefficient values (B) is given below

DI_3 = 6.477 + (.975*D2) ----------(5-4)

Table 5-10 Estimated regression coefficients for general model D_3(g)

Variable	B	Standard error		t		sig	
		Real	Adjusted	Real	Adjusted	Real	Adjusted
Constant	14.91	1.37	1.29	10.89	11.54	.00	.00
DI_2	.93	.05	.09	17.77	10.16	.00	.00
Rol	6.06	1.91	1.89	3.18	3.21	.00	.00
T	-.90	.21	.22	-4.34	-4.13	.00	.00
NP	-.43	.09	.07	-5.03	-6.01	.00	.00

The general model equation 5-4 for damage index year 3 is understood as while controlling for other independent variables, for every additional unit increase in damage index at year 2 there is a corresponding predicted increase of 0.934 units in damage index at year 3.

Summary of general model:

Based on the general model, the choice choosing the AMIR compaction method over CCM would slow down the deterioration rate considerable for the first two years of asphalt pavement service life. Field observations and general model for damage index at years 0 and 1 supports the above statement.

5.1.5 CCM specific model

CCM model ANOVA estimate:

Table 5-11 Summary of ANOVA estimates for CCM model

CCM Model	F	Sig
DI_0CCM	37.52	.00
DI_1CCM	44.27	.00
D_2CCM	275.47	.00
DI_3CCM	109.16	.00

Table 5-11 above provided to show significance of the model fit. Higher F values of the individual model suggest respective model variables possess significant capability to predict their respective *DV*s $DI\_0_{(CCM)}$, $DI\_1_{(CCM)}$, $DI\_2_{(CCM)}$, *and* $DI\_3_{(CCM)}$. Therefore, null hypothesis of not able to predict *DVs* can be rejected at a significance level of 5%.

CCM model performance measure

Table 5-12 Summary of performance measures for CCM model

CCM Model	Adjusted R2	Standard Error of the estimate
DI_0	.66	2.50
DI_1	.37	4.29
DI_2	.92	2.51
DI_3	.59	6.12

The above Table 5-12 provides measures of model fit and prediction values in the form of adjusted R square for the general model for various time periods The coefficient of determination for the combined independent variables and the dependent variable denoted by adjusted R^2 with the respective values of 0.66, 0.37, 0.92 and 0.59 implies that 66%,37%, 92%, and 59% of the variation of respective $DI\_0_{(CCM)}$, $DI\_1_{(CCM)}$, $DI\_2_{(CCM)}$, *and* $DI\_3_{(CCM)}$ could be explained by their respective combined independent variables. The adjusted R^2 accounts for some of the error associated with the model for various independent variables. Finally, a standard error for the estimate that indicates that the variables $DI\_0_{(CCM)}$, $DI\_1_{(CCM)}$, $DI\_2_{(CCM)}$, *and* $DI\_3_{(CCM)}$ that are

estimated by their individual model will deviate from the true value by 2.5, 3.68, 2.34 and 5.69 units.

The heteroscedasticity (non-constant variance) in terms of model residual standard error was adjusted by following the procedure outlined by Hayes, A.F., & Cai, L. This is done to provide reliable model coefficient values and not to be deceived by high R2 values as shown in earlier Table 5-12.

Tables 5-13 to 5-16 provides regression results with coefficient (B), standard error, t-statistics and p-values with and without heteroscedasticity adjustment for standard errors. The regression coefficient of individual independent variables "t" value reveals that the slope of each independent variable is significantly different from zero.

The p-values associated with each independent variable are much smaller than 0.05 showing that each of the model's independent variables is a significant predictor of pavement damage index. Tables 5-13 to 5-16 shows that heteroscedasticity adjustment for standard error has no impact on the model B values, but influence can be seen in standard error, t and p values. The adjusted tables 5-13 to 5-16, values for independent variables are reliable statistically significant predictors with their respective DVs $DI\_0_{(CCM)}$, $DI\_1_{(CCM)}$, $D1\_2_{(CCM)}$ and $DI\_3_{(CCM)}$.

CCM model regression equation

The equation for CCM model damage index for year 0 using later Table 5-13 regression values is given below

$$DI\_0_{CCM} = 39.81+(4.92*Pavt) +(-4.02*T) + (-1.89*NP) +(.29*T\_NP) \text{ ---------(5-5)}$$

Table 5-13 Estimated regression coefficients for CCM DI_0

Variable	B	Standard error		t		sig	
		Real	Adjusted	Real	Adjusted	Real	Adjusted
Constant	39.81	5.20	4.29	7.66	9.27	.00	.00
Pavement type	4.92	.86	.93	5.70	5.31	.00	.00
Mat thickness	-4.02	.89	.79	-4.51	-5.08	.00	.00
Roller passes	-1.89	.24	.20	-7.84	-9.33	.00	.00
Interaction Thickness passes	.29	.04	.04	6.74	7.77	.00	.00

The following is the interpretation of unstandardized regression coefficients relation of various independent variables with dependent variable (DI_0_{CCM}) when controlling for the other independent variables. Equation 5-5 suggests that for every additional unit increase in Pavt and T*NP interaction there is a corresponding predicted increase of 4.92 units and 0.29 units. On the other hand, for every unit increase in T and NP there is a corresponding decrease of 4.02 units and 1.89 units, respectively

In other words, while controlling for other independent variables, granular base pavement type will increase damage index at year 2 by 44.73 (=39.81+4.92) units. Observing equation 5-5 and interpreting that increasing thickness (T) and number of passes on an asphalt mat by a roller will decrease damage index at year 0 is incorrect. A unit increase of asphalt mat thickness (T), number of roller passes on an asphalt mat (NP) and their interaction effect thickness and roller passes will act positively and there is corresponding increase of 35.79 (=39.81-4.02) units, 37.92 (=39.81-1.89) units and 40.1 (=39.81+.29) units in the damage index at year 0 of CCM compacted sections.

The engineering relationship between number of pass of roller on an asphalt mat and thickness of mat is negative on damage index (*DI*). Observation of equation 5-5 confirms that the proper sign has been assigned by the model into the equation. Research works of Abd El Halim et al., (1987), (2006), have shown that quality (construction crack free) passes is required more than the quantity of the passes. The CCM roller's circular shape and the choice of hard steel material, which is a design flaw that generates intense pressure impulse to compact asphalt mat layer thickness. The increased impulse on the asphalt mat and their interaction causes construction cracks, poor compaction at joints and loose surface texture lead to increase in damage index by 35.79 units, 37.92 units, and 40.1 units respectively. It can be concluded that the prediction model supports the theory and findings of that construction cracks reduces the service life of an asphalt pavement.

The equation for CCM model damage index for year 1 given is formed using succeeding Table 5-14 regression coefficient values

$$DI\_1_{CCM} = 7.93 + (.78*DI\_0) \quad \textbf{(5-6)}$$

Table 5-14 Estimated regression coefficients for CCM DI_1

Variable	B	Standard error		t		sig	
		Real	Adjusted	Real	Adjusted	Real	Adjusted
Constant	7.93	1.95	2.02	4.07	3.94	.00	.00
DI_0	.78	.12	.12	6.71	6.63	.00	.00

The following is the interpretation of unstandardized regression coefficients relation of independent variables with dependent variable (DI_1_{CCM}) when controlling for the other independent variables. The equation 5-6 suggest, for every additional unit increase in damage index at year 0 there is a corresponding predicted increase of .78 units in the damage index at

year 1.

The equation for CCM model damage index for year 2 using regression coefficient values from the following Table 5-15 is given below

DI_2 $_{CCM}$ = -7.43 +(1.56*DI_1) +(5.26*Pavt) + (310.09*Perm) ----------(5-7)

Table 5-15 Estimated regression coefficients for CCM DI_2

Variable	B	Standard error		t		sig	
		Real	Adjusted	Real	Adjusted	Real	Adjusted
Constant	-7.43	1.43	1.47	-5.20	-5.06	.00	.00
DI_1	1.56	.05	.05	28.60	29.00	.00	.00
Pavement type	5.26	.73	.65	7.17	5.08	.00	.00
Permeability	310.09	81.76	138.65	3.79	2.24	.01	.03

The regression equation DI_2$_{CCM}$ is interpreted as follows: when controlling for the other independent variable, for every additional unit increase in damage index at year 1, Pavt, and Perm, there is a corresponding predicted increase of 1.56, 5.26 and 310.09 units in damage index at year 2, respectively. In basic words, while controlling for other variables, a unit increase in damage index at year one will correspondingly increase 1.56 units in damage index number at year 2. It is intriguing to observe the increase in damage index at year one obtains a negative effect of -5.87 unit in year 2.

Similarly, depending on pavement type damage index at year 2 is increased by 5.26 unit but the effect is negative -2.17unit. Interestingly, one unit increase in permeability causes a positive effect of 303.47 units in damage index at year 2. Roberts et al. (1991) and Abd El Halim et al.(2016), (2013), (2016) have stated that insufficient asphalt compaction and construction cracks can lead to increased water and air entry in the pavement. Water in the pavement structure leads

to a variety of issues, including stripping and freeze/thaw damage. Air promotes the oxidation of asphalt cement, making the pavement more brittle and susceptible to longitudinal and fatigue cracking, as well as raveling. The above researchers did not indicate exactly when the damage can happen over the life of the road surface. This research thesis has employed models, which have predicted that the damage due to water intrusion will cause a major effect on an asphalt pavement service life at year 2. Knowing the exactly when the impact of water is felt will help road authorities to priorities and act proactively to maintain their asset in a timely manner.

The equation for general model damage index for year 3 using later Table 5-16 regression coefficient values (B) is given below

$$DI\_3_{CCM} = 19.24 + (.82 * DI\_2) \quad (5\text{-}8)$$

The regression equation DI_3_{CCM} is interpreted as when controlling for the other independent variable, for every additional unit increase in damage index at year 2, there is a corresponding predicted increase of 0.82 units in damage index at year 3.

Table 5-16 Estimated regression coefficients for CCM DI_3

Variable	B	Standard error		t		sig	
		Real	Adjusted	Real	Adjusted	Real	Adjusted
Constant	10.30	2.5	2.72	4.13	3.40	.00	.00
DI_2	.85	.08	.10	10.45	9.82	.00	.00

CCM regression model summary

CCM model predicted that the damage effect in CCM compacted sections are caused by pavement type, permeability, thickness, roller passes, interaction effect of roller passes and thickness. Observation of the model equations 5-5 confirms the prediction model (DI_0_{CCM}) since it properly assigned negative relation to the IVs roller passes, thickness of asphalt. Model

calculations have shown that the relationship is positive the CCM roller pass and interaction between roller and mat thickness will increase the damage index. This finding is supported by several research work of Abd El Halim et al. (1991, 2013, 2016) found that CCM roller's design flaw is the reason for the positive relation with DI_0_{CCM}. Roberts et al. (1991) and Abd El Halim et al. (1987, 2006, 2016) have stated that insufficient asphalt compaction and construction cracks can lead to water and air entry in the pavement and can cause severe damage to the pavement. Researchers did not indicate exactly when the damage can happen. This research thesis's CCM model (DI_0_{CCM}) equation 5-7 predicted that the damage due to water intrusion will cause a major effect on an asphalt pavement service life at year 2. Knowing exactly when the impact of water is felt will help road authorities to priorities and act proactively to maintain their asset in timely manner.

5.1.6 AMIR specific model

Table 5-17 provided to show significance of the model fit.

Table 5-17 Summary of ANOVA estimates for AMIR model

AMIR Model	F	Sig
D_0	0	
D_1	28.44	.00
D_2	446.90	.00
D_3	535.26	.00

Higher F values of the individual model suggest respective model variables possess significant capability to predict their respective *DV*s $DI\_0_{(AMIR)}$, $DI\_1_{(AMIR)}$, $DI\_2_{(AMIR)}$, *and* $DI\_3_{(AMIR}$. Therefore, null hypothesis of not able to predicate can be rejected.

AMIR model performance measure estimate

Later Table 5-18 provides multiple correlation coefficient (R) values in the form of adjusted R square for the AMIR model for various time periods. R is a measure of the correlation between the independent variables mentioned in the functional form of the AMIR model.

Table 5-18 Summary of performance measures for AMIR model

AMIR Model	Adjusted R2	Standard Error of the estimate
DI_0	0	0
DI_1	.44	.76
DI_2	.90	.82
DI_3	.84	2.09

equations with their respective $DI\_0_{(AMIR)}$, $DI\_1_{(AMIR)}$, $DI\_2_{(AMIR)}$, *and* $DI\_3_{(AMIR}$ (dependent variable) could be obtained by taking the square root of individual adjusted R square values.

The above Table 5-18 displays the coefficient of determination for the combined independent variables and the dependent variable. It is denoted by adjusted R^2 with the value of 0.44,.90, and.91 which implies that 44%, 90%, and 91% of the variation of respective $DI\_1_{(AMIR)}$, $DI\_2_{(AMIR)}$ and $DI\_3_{(AMIR)}$ could be explained by their respective combined independent variables. Finally, a standard error for the estimate that indicates that $DI\_0_{(AMIR)}$, $DI\_1_{(AMIR)}$, $DI\_2_{(AMIR)}$, *and* $DI\_3_{(AMIR}$ estimated by their individual model will deviate from the true value by 0.76, 0.80, and 1.53 units. The heteroscedasticity (non-constant variance) in terms of model residual standard error was adjusted by following the procedure outlined by Hayes, A.F., & Cai, L. This is done to provide reliable model coefficient values and not to be deceived by the high R^2 values as shown in earlier Table 5-18.

Tables 5-19 to 5-21 provide regression results with coefficient (B), standard error, t statistics and p values with and without heteroscedasticity adjustment for standard errors. The regression coefficient of individual independent variables "t"-value reveals that the partial slope of each independent variable is significantly different from zero.

The p-values associated with each independent variable are much smaller than 0.05 showing that each of the model's independent variables is a significant predictor of pavement damage index. Tables 5-19 to 5-21 shows that heteroscedasticity adjustment for standard error has no impact on the model B values, but influence can be seen in standard error, t and p values. The adjusted tables 5-19 to 5-21 contain values for independent variables, which are reliable and statistically significant predictors with their respective DVs $DI\_0_{(AMIR)}$, $DI\_1_{(AMIR)}$, $D1\_2_{(AMIR)}$ and $DI\_3_{(AMIR)}$.

AMIR model regression equation

The equation for AMIR model damage index for year 0 is given below

$$DI\_0_{AMIR} = 0 \text{ ----------} (5\text{-}9)$$

No construction cracks have been formed by the AMIR roller, which is the reason for elimination of the dependent variable DI_0_{AMIR} from the AMIR specific equation.

The equation for AMIR model damage index for year 1 using regression coefficient values of the following Table 5-19 is given below

$$DI\_1_{AMIR} = 19.97 + (-4.85*NP) + (-.18*Comp) + (.05*(NP*Comp)) \text{ ----------} (5\text{-}10)$$

Table 5-19 Estimated regression coefficients for AMIR DI_1

Variable	B	Standard error		t		sig	
		Real	Adjusted	Real	Adjusted	Real	Adjusted
Constant	19.97	11.33	8.61	1.76	2.32	.08	.02
Roller passes	-4.85	1.88	1.63	-2.58	-2.97	.01	.00
Percent compaction	-.18	.12	.09	-1.47	-1.95	.14	.05
Interaction passes compaction	.05	.02	.02	2.40	2.77	.02	.01

The regression equation DI_1_{AMIR} is interpreted as follows: when controlling for the other independent variables, for every additional unit increase in interaction of NP and Comp, there is a corresponding predicted increase of.049 units in damage index at year 1. On the other hand, every additional increase in NP and Comp there is a corresponding predicted decrease of 4.85 units and 0.18 units in damage index at year 1, respectively.

The engineering relationship between number of roller pass on an asphalt mat and percentage of compaction (density) of an asphalt mat is negative on damage index. Observation of equation 5-10 confirms proper sign has been assigned by the model into the equation. Observing equation 5-10 and interpreting that increasing AMIR roller pass (NP) will eventually increase density of on an asphalt mat will decrease damage index at year 0 is incorrect. A unit increase of AMIR roller pass and its density will act positively and there is corresponding increase of 15.12 (=19.97-4.85) units and 19.79 (=19.97-.18) units in the damage index at year 1 of AMIR compacted sections.

The reason for the positive influence with the damage index (DI_1_{AMIR}) is due to control testing procedure that was adopted in this research study. To determine the optimum roller pass, optimum compaction thickness, optimum compaction temperature for AMIR roller several in-house trial sections were conducted. The trial mats were compacted for different layer thickness, using varying AMIR roller passes and compaction temperature. These test results might have influenced the damage index of AMIR at year 1.

The equation for AMIR model damage index for year 2 using calculated regression coefficient values shown in Table 5-20 is given below

$$DI\_2_{AMIR} = -.50 + (2.00 * DI\_1) + (2.56 * Pavt) \text{ ----------} (5\text{-}11)$$

The regression equation DI_2_{AMIR} is interpreted as follows: when controlling for the other independent variables, for every additional unit increase in damage index at year 1 and depending

on Pavt there is a corresponding predicted increase of 2.00 units and 2.56 units in damage index at year 2, respectively.

Table 5-20 Estimates regression coefficients for AMIR DI_2

Variable	B	Standard error		t		sig	
		Real	Adjusted	Real	Adjusted	Real	Adjusted
Constant	.50	.18	.33	2.76	1.53	.00	.00
DI_1	2.00	.08	.07	24.95	26.92	.00	.00
Pavement type	2.56	.19	.28	13.25	9.14	.00	.00

The equation for AMIR model damage index for year 3 using regression coefficient values of the Table 5-21 is given below

$$DI\_3_{AMIR} = 2.306 + (1.86 * DI\_2) + \text{----------} \quad (5\text{-}12)$$

Table 5-21 Estimated regression coefficients for AMIR DI_3

Variable	B	Standard error		t		Sig	
		Real	Adjusted	Real	Adjusted	Real	Adjusted
Constant	2.31	.43	.61	5.39	3.80	.00	.00
DI_2	1.86	.08	.09	23.14	19.79	.00	.00

The regression equation DI_3_{AMIR} is interpreted as follows: when controlling for the other independent variable, for every additional unit increase in damage index at year 2, there is a corresponding predicted increase of 1.86 units in damage index at year 3.

Summary of AMIR model:

Field observations confirmed that the AMIR roller compacted section had relatively lower deterioration rate than the CCM compacted section. The observation is supported by 0 prediction in damage index at year 0 and at year 1 minor deterioration in comparison with the CCM compacted section is noticeable.

5.1.7 Limitations and other aspects of modelling

In order to statistically model road deterioration and damage, many assumptions have been considered for creating the most effective models. The concepts of road damage and road deterioration have been measured using the dependent variable, DI. For the best modelling results, the data base necessary for creating the model should be as broad and representative as possible, all the significant and relevant variables should be added to the model, and the correct functional form of the model should be specified in order to make the most out of the regression methodology. Sometimes, even though the data is reflective of the expected relationships between the independent variables and the dependent variable, the incorrect functional form would skew the relationship away from the true one, which leads to insignificance of the model variables and the reduction in model prediction measures.

The measurement of DI is assumed to be normally distributed with a mean of the linear regression model and a constant variance across all values of the independent variables. This is a major assumption for creating an effective linear regression model (Field.A, 2012), which also requires that the assumptions be checked once the model is established. The histogram of the dependent variable is approximately symmetrically distributed, which is reasonable for the application of linear regression procedure to obtain the estimated coefficients.

The expected shape of the histograms would be symmetric and would have the mean as the center of the graphs. The histograms of DI in the second and third years are symmetric for both the CCM and AMIR type rollers, hence the assumption of error normality is reasonably satisfied. The DI_3 for CCM and the DI_2 and DI_3 for the AMIR rollers tend to be slightly right skewed, which could be because of the clustering of values closer to 0, since the percentage of cracks did not increase with time at locations HWY 401 and HWY 520.

Next, the concept of sample size is one of the most important aspects that can effectively change

the quality of estimates from a linear regression model (Field.A, 2012). The total number of effective observations used in the model is 180, which includes the different locations (highways) and the measurements for four different time periods (years 0, 1, 2, 3). The sample size could have been higher to come up with the more precise and effective estimates for the prediction of damage index. The regression model works better for large sample sizes so that the effective relationships can be observed for the data. Maybe more measurements for each time period could be obtained, which can be done by increasing the number of highways that have been sampled over this process. Another way to improve the estimates is to increase the number of replicates for each highway and time period so that the effective sample size can be made higher as a result.

Furthermore, to improve the ways in which observations have been collected, a sampling frame could be chosen so that the observations are chosen within the set of previously accepted places and locations. The highways have been chosen by the Ministry of Transportation based on those highways and roads over which the AMIR roller has been tried and tested upon. The process by which these locations were chosen is not a truly random process, which needs to be mentioned and should be improved in future studies. The variability among the locations should be reflective of the variability among all roads across different provinces in Canada. The truly random and representative sample is also one of the major assumptions of the linear regression estimates, which reflect the quality and strength of the relationship between the independent variables and the dependent variable, DI.

In terms of the variables used in the model, many variables are related to the reliability of the pavement and the roads such as the stress and strain factors that can accurately explain the deterioration and decline in the road conditions over a period. The measurement and quantification of cracking has been completed using the DI, which is a scale variable that

contains measurements for the various levels of damage and deterioration from 0 to 5 in integer values. Most of the DI measurements have been completed by making use of the observational skills of the researcher, which also implies that there is a lot of subjectivity on the matter.

However, it must be stated that the international standard for observing cracks is through this scale that has been using in this study. This should be improved to make use of a scale measurement on the continuous scale that can take into the account the various differences among the cracking surfaces to distinguish them from each other. This would greatly improve the regression estimates as the linear regression methodology assumes that the dependent variable is continuous and without discretized levels. For this, a new measure needs to be developed that can take into account the different ways to measure cracking and road deterioration.

The statistical models obtained for the general model, CCM-specific model, and AMIR-specific model could be compared with similar models from other research studies, which would improve the prediction levels of the dependent variables and provide explanation for various interesting trends. However, the data collected in this study does not contain the many variables that have been utilized in the major research studies referenced in this thesis. As a result, it would be better to fit a model using the data that has been collected by other studies to check for comparable trends and descriptions of the various relationships among the *IVs* and the *DVs* provided in the studies.

5.1.8 Conclusions

The larger number of cracks visible in time period 0 with the CCM roller is a major issue across the world in terms of highway engineering. During the starting period at time 0, the AMIR roller did not show any construction cracks. The development of cracks took a much longer time horizon when compared to the CCM. This should be taken care of soon to prevent the loss of

structural integrity of the road systems, for which replacement of the CCM roller with the AMIR roller seems to be a reasonable choice.

Based on the general model, the choice choosing the AMIR compaction method over CCM would slow down the deterioration rate considerable for the first two years of asphalt pavement service life. Field observation and general model for damage index at years 0 and 1 supports the above statement. The performance of the AMIR roller is usually superior to the CCM roller, along with a much lower maintenance over the period of 3 years.

CCM model calculation revealed the relationship between the CCM roller pass, thickness and interaction between roller and mat thickness will increase damage index. The finding is supported by several research work of Abd El Halim et al. (1985, 2006, 2013).

Research work of Roberts et al., (1991) and Abd El Halim et al., (1985, 2006, 2013) state that water and air entry into an asphalt pavement can cause severe damage. Researchers did not indicate exactly when the damage could be felt. This research thesis of CCM model (DI_2_{CCM}) predicted that the damage due to water intrusion will cause a major effect on an asphalt pavement service life at year 2. Knowing exactly when the impact of water is felt will help road authorities to priorities and act proactively to maintain their asset in timely manner.

5.2 Economic Analysis

Appropriate use of resources and efficient time management are necessary to control the cost of any construction project. From previous sections, it is evident that quality of compacted surface could be achieved by either method; however, the resources that are required differ between the two methods. This section provides a general estimate of the hourly cost of the AMIR roller and assesses the most economic compaction method in terms of time, manpower, and equipment all of which are necessary for construction management.

5.2.1 Hourly cost for compacting asphalt using AMIR technology

As mentioned in section 3.3 of this study, the economic analysis is done to find the most efficient compaction method that will be done using the schedule of rental rates from the OPSS No. 127 (Ministry of Transportation Ontario, 2015) specification. According to this specification, hourly equipment rates are calculated using the direct and indirect costs of owning and operating the equipment. Operator costs are not included in the calculations.

The rental rate for new technological equipment will always be high due to a high initial purchase cost considering less production. Moreover, trying to estimate the salvage value and service life of new equipment will be a challenge due to an absence of previous performance history. There are several ways to calculate equipment hourly rate. Two methods (depreciation value, OPSS rates) are explored in this study was selected. Since the salvage value and service life of the AMIR roller cannot be accurately estimated (due to a lack of performance history), this study compensates by choosing the calculation method that yields higher hourly rental rate.

Method 1:

The following steps were applied to get the rental rate per hour for the AMIR roller using depreciation value and variable cost:

1) Determine depreciation value for the working hours of the AMIR roller by assuming a linear decline in value adopting the logical formula below (Food and Agricultural Organization of the United Nations , 1992).

$$D = ((P' - S)) \ / \ N \qquad (5\text{-}13)$$

Where,

D = depreciation value in $/hour

P' = initial purchase price in $

S = salvage cost in $

N = economic service life in working hours. The economic service life is the period over which the used equipment can operate at an acceptable operating cost.

(2) Adjust the purchase cost of the roller by - 30%. This is the assumed value for cost of fuel, lubrication, insurance, repair & maintenance. Divide the adjusted value by the economic service life to find the operating cost, expressed in working hours.

$$Variable\ cost = (P' \times 0.3)\ /\ N \qquad (5\text{-}14)$$

Where,

P' = initial purchase price in $

N = economic service life in working hours.

(3) Add the depreciation and operating costs to get the rental rate in dollar per hour for the AMIR roller.

Later Table 5-22 shows the estimated of rental rate for the AMIR roller using the depreciation value method. For calculation purposes, $500,000 was used as the initial purchase price (P') for the AMIR roller (Tomlinson Group Ltd, 2018). The salvage value (S) is assumed to be 10% of the initial purchase price (Food and Agricultural Organization of the United Nations , 1992).

Table 5-22 Estimation of hourly rental cost of the AMIR using depreciation

Aspects	Assumptions	Sum
Purchase cost (P')	$500,000	
Salvage cost (S)	$50000	
Economical service life (N)	3456 hours	
Depreciation cost (P'-S)/N		$130.21
+ variable cost of AMIR roller (P'× 0.3)/N		$43.40
AMIR hourly rental rate		$173.61

The economic service life (N) 3456 (=9*128*3) hours is calculated by using a conservative assumption of 9 working hours a day in a year of 128 days for a three-year period. Paving season for a year according to the Ontario Provincial Specification Standards considered is six months

(from May- October) or 128 days.

As explained in Chapter 2 of this study, the AMIR roller's main contact area with asphalt mat is made up of multi-layer rubber belt. Rubber is a sensitive material. It can be punched or pierced if handled roughly during freight (loading and unloading) or on-site (driving roller over boulders). Therefore, a conservative estimate of 3 years is used as life period for the rubber belt.

Method 2:

The following steps applied to obtain a rental rate for the AMIR roller using OPSS 127 rates of the conventional roller:

(1) Find the individual hourly total cost of each of the three conventional rollers using the OPSS No. 127 rates (Ministry of Transportation Ontario, 2015).

(2) Adjust the hourly total cost of each of the three conventional rollers by - 47%.This is the rounded sum of the estimated value for the operating cost for roller in terms of fuel, lubrication, insurance, repair and maintenance: -26.7%, -5.3%, -1.6% & -13.3% respectively (Equipment World, 2010)

(3) Compute the individual owning cost (procurement cost) for each of the three conventional rollers by subtracting the operating cost from the hourly rate of each roller.

(4) Sum the owning cost (procurement cost) of the three conventional rollers.

(5) Add the operating cost of the AMIR; obtained from the average of the operating costs of the three conventional rollers. This will be the economic hourly rate of the AMIR roller.

Later Table 5-23 presents the above steps, which were used in calculating the AMIR roller rates using OPSS 127 rental rates for the CCM rollers. Estimated rental cost for the AMIR roller found by using depreciation value and by using the OPSS rental rates for the conventional roller are $173.61 (Table 5-22) and $173.31 (Table 5-23). The higher hourly rate produced by the

depreciation value method ($173.61 rounded to $173.60) is the rate selected as the hourly rental rate for the AMIR roller for the purposes of this study.

Table 5-23 Estimation of hourly rental cost of the AMIR using OPSS 127 rates

Aspects	**Conventional rollers**				**AMIR roller**
Roller type	**Static**	**Pneumatic**	**Vibratory**	**Average**	**AMIR**
Minimum weight in ton	10	18	12		10
OPSS 127 hourly rate	$52.85	$91.90	$107.65		NA
- Operating cost	($24.84)	($43.19)	($50.60)	$39.54	NA
= Owning (procure)cost	$28.01	$48.71	$57.05		$133.77
+ Operating cost of AMIR Roller					$39.54
AMIR economical hourly rate					$173.31

5.2.2 Equipment cost for compacting granular base asphalt:

The activities involved in site preparation for the trial sections are described in Chapter 1 of this study. In order, to calculate the hourly equipment cost for compacting a 40-50mm lift thickness of asphalt mix on granular base the following procedure is applied:

(1) For calculation purpose, equipment needs kept to a constant for one crew.

(2) Identify the key equipment used in on-site for each compaction type and apply the rental cost.

(3) Multiply the hourly rate of equipment by the number of equipment used.

(4) Sum the hourly cost of adaptive equipment under each compaction type to obtain the total hourly cost.

Table 5-24 Hourly equipment cost to compact granular base layer

Equipment	Hourly rate	No	Compaction Type	
			CCM	AMIR
Static tandem smooth drum roller	$52.85	1	$52.85	
Vibratory tandem drum roller	$107.65	1	$107.65	
Pneumatic tire roller	$91.90	1	$91.90	
AMIR roller	$173.60	1		$173.60
Detachable gooseneck tractor with float	$124.90	2/1	$249.80	$124.90
Water truck single rear axle	$80.35	1	$80.35	
Total hourly cost			$582.55	$298.50

The previous Table 5-24 illustrates that there is a net saving of 48.76 % or $284.05 per hour, in equipment costs by adopting the AMIR compaction method. The savings in the AMIR method is primarily due to the elimination of equipment like water trucks, additional rollers, and a float. Water is used to increase the weight of the CCM rollers and as a release agent to avoid sticking of asphalt to the CCM rollers. Consequently, a water truck and an operator are mandatory for the CCM compaction. Since there are extra rollers in the CCM method, an additional float is needed to bring the paving machine to the site. In the case of the AMIR method, a paver and the roller can be pooled in the same freight.

5.2.3 Manpower cost to compact granular base asphalt layer

Statistics Canada (2016) publishes the national hourly rates for trades and equipment operators annually. The average operator rate by the Statistics Canada was at $24.99/hour. Further comparison with current trends in the construction industry conducted to determine the accuracy of the operator rate provided by the Statistics Canada. Most construction workers are employed seasonally. New company employees are not union members, though established highway construction company trades, and equipment employees are unionized. According to the

Statistics Canada website (Statistics Canada, 2016), the hourly rate for a union employee is $30.58. For non-union members, it is $24.33, and for temporary employees $20.64. The hourly operator rate determined by Statics Canada as $24.99 is acceptable as a reasonable rate that adequately reflects industry trends. For calculation purposes, this study set the operator rate at $25/ hour.

In order, to calculate the hourly manpower cost for compacting a 40-50mm lift thickness of asphalt mix on a granular base following procedure applied:

(1) Proliferate the assumed hourly rate of an operator by the possible number of necessary equipment used.

(2) Sum the hourly rate of an operator under each compaction type to get the total hourly cost.

As shown in later Table 5-25, the total hourly cost of the operators required for the standard CCM method is precisely $150.00, and for the comparative AMIR method it is $50. Therefore, a manpower savings of 66.67% or $100 per hour can be achieved by using the AMIR method.

Table 5-25 Hourly manpower cost to compact granular base asphalt layer

Equipment	Hourly rate	No	Compaction Type	
			CCM	AMIR
Static tandem smooth drum roller	$25	1	$25	
Vibratory tandem drum roller	$25	1	$25	
Pneumatic tire roller	$25	1	$25	
AMIR roller	$25	1		$25
Detachable gooseneck float with tractor	$25	2/1	$50	$25
Water truck single rear axle	$25	1	$25	
Total hourly equipment cost			$150	$50

5.2.4 Cost for compacting bridge deck asphalt overlay

As discussed in Chapter 1 of this research study, the equipment required for compacting the asphalt overlay on a bridge deck differs significantly compared to that of a granular base. This section will explain the unbiased estimate for time, equipment and human resources conserved during the compaction process of paving concrete base pavement.

Chapter 3 of this study outlines the laying procedure. The Ministry contractors laid asphalt overlay on bridge decks on the Highways 7, 520 and 401 in two separate lifts of 40-45mm. The process of laying and compacting the asphalt, as outlined in OPSS No. 313 (Ministry of Transportation Ontario, 2015), followed promptly. The following procedure applied to calculate the equipment time, costs for equipment, and workforce required to compact asphalt overlay on a bridge deck for a length of 500 meters, a width of 1.73 meters and thickness of 50mm per layer:

(1) Hours of operation of the equipment is calculated based on the operating speed of 4 km/hour.

(2) Time required per pass is calculated based on the following formula:

$$Time = (Distance\ travel\ (Km))/(\text{Operating speed(Km/hr)}) \qquad (5\text{-}15)$$

(3) The average passes observed during the compaction of asphalt overlay on the bridge decks on the Highways 7, 34, 520 and 401 is used to obtain the number of passes.

(4) Proliferate time/pass with the number of passes and number of layers to find the compaction time per hour for each roller.

(5) Idle time: According to OPSS No. 313 (Ministry of Transportation Ontario, 2015) the bottom layer must be cooled to a temperature of 50°c or lower to receive the topmost layer. In the bridge deck asphalt overlay, due to construction staging restriction, it was observed in the Highways 7, 520 and 401 that the paving crew and machinery were kept idle for a minimum of

4 hours during the cooling period of the base layer. For calculation purposes, an idle time of 4 hours is used as the cooling period.

(6) Sum the actual compaction and idle times to get total time of each roller.

(7) A Static or finish roller passes start at the completion of a pneumatic roller. Therefore, static roller working hours will be higher than the pneumatic roller.

(8) Water truck and the static roller working hours are considered the same. The same hours of operation are due to water truck operator perform other tasks like cleaning and temporary road marking.

(9) Float time includes equipment load time at the end of work.

(10) Equipment and manpower costs are calculated by multiplying equipment hour with the number of machinery or workforce and rental rate per hour.

Tables 5-26 to 5-28 show the total time equipment and workforce costs required for compacting two lifts of asphalt mat over the bridge deck. The time needed to compact two asphalt lifts over the bridge deck by the AMIR methods is 65.2% lower than the CCM as reported in later Table 5-26.

Table 5-26 Time required to compact two layers of asphalt mat over a bridge deck

Equipment	**No of lift**	**Pass**	**Time/Pass (hr)**	**Compaction time (hr)**		**Total time (hr)**	
				Actual	**Idle**	**CCM**	**AMIR**
Pneumatic	2	18	0.125	4.5	4	8.5	
Static	2	4	0.125	1	4	8.75	
AMIR	2	8	0.125	2	4		6
				Total time		17.25	6

Table 5-27 Equipment cost to compact two layers of asphalt mat over a concrete base

Equipment	No	Time (hr)	Rate ($/hr)	CCM ($)	AMIR ($)
Pneumatic	1	8.5	91.90	781.15	
Static	1	8.75	52.85		
AMIR	1	6	173.60		1041.60
Water truck	1	8.75	80.35	703.06	
Float for CCM	1	9.0	124.50	1120.5	
Float for AMIR	1	6.15	124.50		765.68
Cost (rounded)				3067.15	1807.30

Table 5-28 Workforce cost to compact two layers of asphalt mat over a bridge deck

Manpower	No	Time (hr)	Rate ($/hr)	CCM ($)	AMIR ($)
Pneumatic	1	8.5	25	212.5	
Static	1	8.75	25	218.75	
AMIR	1	6	25		150.00
Water truck	1	8.75	25	218.75	
Float for CCM	1	9.0	25	225.00	
Float for AMIR	1	6.15	25		153.75
Cost (rounded)				875.00	303.75

The earlier Tables 5-27 and 5-28 shows the AMIR method is 41.1% and 65.3% lower than the CCM in terms of equipment and workforce cost respectively. Currently, in Ontario asphalt overlay on a concrete bridge deck is laid as two separate layers with a thickness of 50mm and

40mm by following OPSS No.313. The AMIR compaction method is capable of compacting 90-100mm of asphalt layer thickness as a single layer. The in-house granular base field trials confirmed the findings. The HWY 34 trial demonstrates the AMIR roller's ability to compact one single thick layer of 90-100mm asphalt mat under cold weather conditions on a concrete base.

The HWY 34 trial section of the CCM method was compacted following OPSS No.313 under a perfect sunny weather condition in two separate layers 50mm (bottom) and 40mm (Top). The AMIR method trial section of HWY 34 was done one month later to due construction staging. The AMIR section was compacted with a single layer thickness of 90mm, under cold weather condition of -1°C to – 3°C. Tables 5-29 to 5-31 present the possible time and costs of equipment and workforce by the CCM and the AMIR methods to compact the HWY 34 bridge deck asphalt overlay.

The subsequent Tables 5-29 to 5-31 clearly show that the AMIR method is the more efficient and sustainable way to compact asphalt mat. This claim is supported by a 94.2% reduction in compaction time, an 89.7% reduction in equipment costs, and a 93.9% reduction in manpower cost.

Table 5-29 Time required to compact asphalt overlay on HWY 34 bridge deck

Equipment	**No of lift**	**Pass**	**Time/Pass (hr)**	**Compaction time (hr)**		**Total time (hr)**	
				actual	**Idle**	**CCM**	**AMIR**
Pneumatic	2	18	0.125	4.5	4	8.5	
Static	2	4	0.125	1	4	8.75	
AMIR	2	8	0.125	1	0		1
				Total time		17.25	1

Table 5-30 Cost of equipment to compact asphalt overlay on HWY 34 bridge deck

Equipment	No	Time (hr.)	Rate ($/hr.)	CCM ($)	AMIR ($)
Pneumatic	1	8.5	91.90	781.15	
Static	1	8.75	52.85		
AMIR	1	1	173.60		173.60
Water truck	1	8.75	80.35	703.06	
Float for CCM	1	9.0	124.50	1120.5	
Float for AMIR	1	1.15	124.50		143.18
Cost (rounded)				3067.15	316.80

Table 5-31 Manpower cost to compact asphalt overlay on HWY 34 bridge deck

Manpower	No	Time (hr.)	Rate ($/hr.)	CCM ($)	AMIR ($)
Pneumatic	1	8.5	25	212.50	
Static	1	8.75	25	218.75	
AMIR	1	1	25		25.00
Water truck	1	8.75	25	218.75	
Float for CCM	1	9.0	25	225.00	
Float for AMIR	1	1.15	25		28.75
Cost (rounded)				875.00	53.75

5.2.5 Cost saving from Maintenance:

A long-term performance review of trial sites (three to five years) shows that the CCM method compacted asphalt pavement centerline joint received critically preventive maintenance. The early need for minor maintenance is due to the presence of centerline crack. The manual for

condition rating SP024 (Ministry of Transportation Ontario, 1989) notes that centerline cracks may be due to poor joint construction practice. The centerline joint crack was noticeable in most of the CCM trial locations. The AMIR method compacted trial sections had no centerline or longitudinal cracks in most of the trial locations. A brief review of the long-term performance of the individual trial sites is explained later in this doctoral thesis.

The standard practice of preventive maintenance for centerline crack according to SP024 is route and seal. The effective procedure and equipment needs are outlined in OPSS No.341 (Ministry of Transportation Ontario, 2015).

Table 5-32 Equipment and manpower cost of preventive maintenance

Equipment	No	Time (hr)	Rate ($/hr)	CCM ($)	AMIR ($)
Pavement Router	1	4	10.55	42.20	0
Hot air lance	1	4	9.85	39.40	0
Mastic kettle	1	4	29.35	117.40	0
Air compressor	1	4	43.40	173.60	0
Pickup four-wheel drive	1	4	30.30	121.20	0
Manpower	4	4	25	100.00	0
Traffic control		Excluded			
Total cost				593.80	0

The preceding Table 5-32 details equipment and manpower cost for sealing centerline joints using the OPSS No.127 rate (Ministry of Transportation Ontario, 2015). A pickup truck included in the estimate in order to transport the equipment and manpower to the job site. Traffic control is excluded from the estimate as OPSS No.127 rates do not include this item. The AMIR method

clearly saves 100% of centerline preventive maintenance.

In conclusion, the AMIR technology is capable of saving time, machinery and workforce for both granular and concrete bases. Adopting the AMIR technology will help the highway construction industry to achieve sustainability in the paving process by eliminating currently critical equipment namely vibratory rollers, tire rollers, water trucks and extra floats. All Provinces in Canada are mandated by the federal government to implement a provincial carbon tax in 2019. By willingly embracing the more efficient AMIR method, the highway construction owners could save more money on carbon tax by producing fewer direct emissions.

Moreover, the potential savings from reduced equipment, human resources and carbon tax will help to minimize the paving cost. Independent contractors can pass over the operational savings to the taxpayers in the form of lower bid prices when biding for the government road construction projects. The savings potential from eliminating premature centerline preventive maintenance could be passed from the road authorities to the taxpayers. For example, by focusing on the much-needed road expansion projects that could reduce travel time. Therefore, adopting AMIR technology will represent a win-win situation for the community.

Chapter 6 : Conclusions and Recommendations

6.1 Conclusions

The conclusions of the work performed in this research can be grouped into the following seven topics:

(1) Percent compaction of two compaction techniques

The CCM and AMIR compaction methods are capable of meeting the minimum compaction requirement set by the Ontario provincial road authority in OPSS No.313. However, the Falling Weight Deflectometer test showed that the AMIR compacted pavement strength was improved by at least 6%.

(2) Permeability

The AMIR compaction method showed reduced permeability than the CCM compacted section pavements on both granular and bridge concrete bases. The higher level of CCM permeability can be due to the influence of construction cracks induced by the conventional compaction equipment. The need for permeability standards was apparent when comparing individual field permeability trial mean values to standard value set by the Queensland Department of Transportation and Main Roads, Australia.

(3) Indirect tensile strength:

The indirect tensile strength test results showed that the AMIR technology improved the strength of its compacted sections by an overall average of 19.5% higher than that achieved by the CCM on same mixes. This result demonstrates that the concept of using longer duration, flat roller surface contacts with asphalt mat can increase the mat strength higher than roller contacts of circular and short duration. Moreover, the increase in mat strength was achieved using a single AMIR roller with fewer passes than the combined CCM rollers.

(4) Optimum Requirement of the AMIR Compaction Technique

In-house and provincial highway trials confirmed that the AMIR roller compaction technology is capable of compacting 95-100 mm thick mat at 90-95°c compaction temperature with a maximum of eight passes and an average thickness of 70mm at same temperature in two passes. This is in comparison with at least 20 passes by CCM to achieve comparable densities.

(5) Mathematical Model for Compaction

The research hypothesis considered here— "the likelihood of compaction method influence on pavement distress and permeability"— is supported by the results of the regression models. Field observation and general models for damage index supports the choice of the AMIR compaction method over the CCM due to slower deterioration rate and lower maintenance over the period of six years in the asphalt pavement service life. This research thesis of CCM model (DI_2CCM) predicted that the damage due to water intrusion will cause a major effect on an asphalt pavement service life at year 2. This damage model is being significant since most of the current models which have been developed to predict asphalt deterioration are considered sub optimal.

(6) Economic Analysis

The AMIR technology can save time, machinery and workforce for asphalt pavement granular and concrete bases. Adopting the AMIR technology can help the highway construction industry achieve sustainability. Moreover, it will improve construction zone safety during the paving process by eliminating equipment, including vibratory rollers, tire rollers, water trucks and extra float (freight). The federal government has mandated that all provinces in Canada to implement a provincial carbon tax in 2019. By using the AMIR method, highway contractors could recover money from the carbon tax due to reduced emissions. It is important to note that at the present time a new design is developed where contractors will be offered the opportunity to replace the large drums of their current steel roller by 4 kits assembling an AMIR type. Thus, adopting the

AMIR compaction method will result in reducing the initial investment significantly.

(7) Evaluation of Long-Term Performance

Pavement edge cracks were visible in the granular base sections of both the CCM and AMIR trial locations without lateral support. Longitudinal and centerline cracks related to compaction, were evident in the CCM trial sections, while the AMIR compacted sections had no visible cracks. The AMIR compacted mat possesses lower ravelling in most of the trial sites compared to the CCM. It can be concluded that poor compaction of the asphalt may be the reason for the ravelling, centerline and longitudinal cracks in the CCM section

6.2 Recommendations:

(1) This research study recommends paving a thicker mat (80-100mm) to reduce longitudinal and transverse joints. Reducing joints will reduce asphalt pavement laying cost and construction time. The research trials showed that the AMIR technology could compact thicker mats at lower air temperature of -1° to -3°c. Further trials needed to confirm the consistency.

(2) The research study recommends testing joint compaction to prevent premature failure. Specifying a minimum joint compaction level about 2 percent, less than the mat as prescribed by the Federal Highway Administration ((Pavement Interactive, 2018) would be a good start.

(3) Surface permeability depends on the compaction and highway pavement materials. This study recommends adding nondestructive field permeability testing into the road authority protocols to enhance acceptance quality criteria.

(4) It is recommended to increase inspection while filling and compacting core holes. Appendix 4 displays poor compaction of core holes.

(5) Permeability testing should to be performed on fresh cool asphalt mat before local traffic is allowed. This study recommends automation of the testing apparatus to efficiently capture essential points with reduced time and cost.

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Appendices

Appendix 1 Data of multiple regression

ID	Pavement	Perm	Comp	Rol	T	Passes	IDS	D_0	D_1	D_2	D_3
1	Granular	0.004583	86.24	CCM	5.73	10	293.51	20	20	28	40
2	Granular	0.003634	88.30	CCM	5.23	10	318.05	20	20	28	40
3	Granular	0.002984	89.32	CCM	5.20	10	320.78	20	20	28	40
4	Granular	0.001127	90.33	CCM	4.95	10	368.93	20	20	28	40
5	Granular	0.00104	91.48	CCM	4.78	10	431.6	20	20	28	40
6	Granular	0.000433	93.34	CCM	4.58	10	462.14	20	20	28	40
7	Granular	0.000433	93.34	CCM	4.53	10	479.61	20	20	28	40
8	Granular	0.000343	93.38	CCM	4.05	10	489.36	20	20	28	40
9	Granular	0.000148	93.39	CCM	3.83	10	544.83	20	20	28	40
10	Granular	0.000141	94.12	CCM	3.83	10	623.8	20	20	28	40
11	Granular	0.001152	88.36	CCM	7.80	12	467.7	20	20	28	38
12	Granular	0.002028	89.14	CCM	7.40	12	472.87	20	20	28	38
13	Granular	0.0029	89.95	CCM	7.00	12	493.28	20	20	28	38
14	Granular	0.003589	90.52	CCM	6.40	12	533.32	20	20	28	38
15	Granular	0.004822	90.89	CCM	6.30	12	689.35	20	20	28	38
16	Granular	0.005102	92.15	CCM	5.80	12	697.21	20	20	28	38
17	Granular	0.001152	92.15	CCM	5.80	11	697.21	20	20	28	38
18	Granular	0.0145	87.73	CCM	5.00	22	61.16	16	22	38	46.25
19	Granular	0.0124	88.00	CCM	5.00	22	257.58	16	22	38	46.25
20	Granular	0.0102	90.00	CCM	5.00	22	314.46	16	22	38	46.25
21	Granular	0.007482	90.00	CCM	5.00	22	340.35	16	22	38	46.25
22	Granular	0.006409	90.51	CCM	5.00	22	390.86	16	22	38	46.25
23	Granular	0.0056	90.98	CCM	5.00	22	403.95	16	22	38	46.25
24	Granular	0.005276	91.00	CCM	5.00	22	437.55	16	22	38	46.25

25	Granular	0.00314	91.00	CCM	5.00	22	453.62	16	22	38	46.25
26	Granular	0.00176	91.18	CCM	5.00	22	460.73	16	22	38	46.25
27	Granular	0.001409	91.45	CCM	5.00	22	467.66	16	22	38	46.25
28	Granular	0.001172	91.80	CCM	5.00	22	494.99	16	22	38	46.25
29	Granular	0.001044	92.00	CCM	5.00	22	636.44	16	22	38	46.25
30	Granular	0.00044	92.00	CCM	5.00	22	659.33	16	22	38	46.25
31	Granular	0.000744	93.87	CCM	5.00	22	226.41	10	13	17	25.5
32	Granular	0.000612	93.55	CCM	5.00	22	238.85	10	13	17	25.5
33	Granular	0.000479	94.07	CCM	5.00	22	241.58	10	13	17	25.5
34	Granular	0.000358	93.39	CCM	5.00	22	245.54	10	13	17	25.5
35	Granular	0.000336	93.19	CCM	5.00	22	254.01	10	13	17	25.5
36	Granular	0.000189	93.31	CCM	5.00	22	272.99	10	13	17	25.5
37	Granular	0.000157	93.39	CCM	5.00	22	302.84	10	13	17	25.5
38	Granular	0.00013	93.31	CCM	5.00	22	363.89	10	13	17	25.5
39	Granular	0.000109	91.98	CCM	5.00	22	363.91	10	13	17	25.5
40	Granular	0.000048	92.06	CCM	5.00	22	398.6	10	13	17	25.5
41	Concrete	0.004976	92.78	CCM	8.00	18	313.92	12	24	33.5	45.5
42	Concrete	0.003317	92.12	CCM	8.00	18	313.92	12	24	33.5	45.5
43	Concrete	0.004146	92.25	CCM	8.00	18	313.92	12	24	33.5	45.5
44	Concrete	0.006235	92.55	CCM	8.00	18	313.92	12	24	33.5	45.5
45	Concrete	0.004879	93.00	CCM	8.00	18	313.92	12	24	33.5	45.5
46	Concrete	0.004316	93.32	CCM	8.00	18	313.92	12	24	33.5	45.5
47	Concrete	0.00622	93.45	CCM	8.00	18	313.92	12	24	33.5	45.5
48	Concrete	0.0193	88.18	CCM	9.00	24	187.17	20	28	36	32.33
49	Concrete	0.002525	88.55	CCM	9.00	24	211.4	20	28	36	32.33
50	Concrete	0.002087	89.16	CCM	9.00	24	460.73	20	28	36	32.33
51	Concrete	0.0162	90.00	CCM	4.00	24	119.1	8	9.5	10	10
52	Concrete	0.0102	90.12	CCM	4.00	24	254.01	8	9.5	10	10

53	Concrete	0.00788	90.35	CCM	4.00	24	272.99	8	9.5	10	10
54	Concrete	0.0073	91.00	CCM	4.00	24	363.91	8	9.5	10	10
55	Concrete	0.00516	91.20	CCM	4.00	24	460.73	8	9.5	10	10
56	Concrete	0.006604	90.00	CCM	8.00	24	294.15	20	28	36	32.25
57	Concrete	0.002896	91.00	CCM	8.00	24	177.62	20	28	36	32.25
58	Concrete	0.002525	93.00	CCM	8.00	24	226.41	20	28	36	32.25
59	Concrete	0.002087	94.00	CCM	8.00	24	363.89	20	28	36	32.25
60	Concrete	0.000241	94.00	CCM	8.00	24	437.55	20	28	36	32.25
61	Granular	0.00371	88.50	CCM	5.00	15	70.77	18	30	42	33.25
62	Granular	0.002472	89.48	CCM	5.00	15	86.87	18	30	42	33.25
63	Granular	0.002266	90.75	CCM	5.00	15	89.24	18	30	42	33.25
64	Granular	0.001087	91.84	CCM	5.00	15	90.02	18	30	42	33.25
65	Granular	0.000485	93.82	CCM	5.00	15	93.15	18	30	42	33.25
66	Granular	0.000392	88.00	CCM	7.00	24	72.99	20	20	29	33.5
67	Granular	0.000322	89.00	CCM	6.60	24	106.31	20	20	29	33.5
68	Granular	0.000309	89.00	CCM	6.50	24	111.75	20	20	29	33.5
69	Granular	0.000266	90.00	CCM	5.80	12	112.94	20	20	29	33.5
70	Granular	0.000191	90.00	CCM	5.70	24	117.4	20	20	29	33.5
71	Granular	0.000142	90.00	CCM	5.50	18	127.74	20	20	29	33.5
72	Granular	0.000131	91.00	CCM	5.50	12	146.29	20	20	29	33.5
73	Granular	0.000128	91.00	CCM	5.40	18	147.31	20	20	29	33.5
74	Granular	0.000108	92.00	CCM	5.40	18	241.58	20	20	29	33.5
75	Granular	0.00002	92.00	CCM	5.20	12	302.84	20	20	29	33.5
76	Granular	0.00002	93.00	CCM	5.00	12	347.88	20	20	29	33.5
77	Granular	0.0175	86.16	AMIR	6.58	4	195.98	0	2	7	16
78	Granular	0.0153	87.67	AMIR	6.33	4	292.17	0	2	7	16
79	Granular	0.0135	89.25	AMIR	6.33	4	314.74	0	2	7	16
80	Granular	0.0111	89.25	AMIR	6.18	6	395.68	0	2	7	16

81	Granular	0.0111	90.48	AMIR	6.18	2	438.16	0	2	7	16
82	Granular	0.00994	91.28	AMIR	5.78	2	450.14	0	2	7	16
83	Granular	0.00994	91.71	AMIR	5.68	2	451.4	0	2	7	16
84	Granular	0.00994	91.99	AMIR	5.50	4	459.58	0	2	7	16
85	Granular	0.00994	91.99	AMIR	5.50	4	507.81	0	2	7	16
86	Granular	0.00921	92.47	AMIR	5.43	6	511.25	0	2	7	16
87	Granular	0.00876	93.46	AMIR	5.43	6	562.11	0	2	7	16
88	Granular	0.00732	93.46	AMIR	5.23	2	562.95	0	2	7	16
89	Granular	0.00491	93.70	AMIR	5.20	4	589.45	0	2	7	16
90	Granular	0.00466	93.93	AMIR	5.15	6	600.58	0	2	7	16
91	Granular	0.00314	93.93	AMIR	5.05	6	656.14	0	2	7	16
92	Granular	0.00251	93.93	AMIR	5.00	4	721	0	2	7	16
93	Granular	0.00161	94.13	AMIR	5.00	6	738.43	0	2	7	16
94	Granular	0.00159	94.57	AMIR	5.00	6	739.75	0	2	7	16
95	Granular	0.00159	94.57	AMIR	5.00	6	803.2	0	2	7	16
96	Granular	0.0014	94.61	AMIR	5.00	6	1024.21	0	2	7	16
97	Granular	0.00101	94.61	AMIR	5.00	4	471.66	0	2	7	16
98	Granular	0.000854	94.73	AMIR	5.00	6	720.08	0	2	7	16
99	Granular	0.000707	94.73	AMIR	5.00	4	780.12	0	2	7	16
100	Granular	0.000707	94.77	AMIR	4.98	4	216.93	0	2	7	16
101	Granular	0.000608	95.52	AMIR	4.98	4	208.42	0	2	7	16
102	Granular	0.000548	95.52	AMIR	4.78	4	370.05	0	2	7	16
103	Granular	0.000264	95.72	AMIR	4.33	2	547.01	0	2	7	16
104	Granular	0.000182	97.58	AMIR	4.18	4	720.08	0	2	7	16
105	Granular	0.000111	97.82	AMIR	4.03	6	745.43	0	2	7	16
106	Granular	0.000322	93.00	AMIR	7.80	6	314.46	0	1	6	12
107	Granular	0.0005	93.00	AMIR	7.40	6	406.54	0	1	6	12
108	Granular	0.000563	93.00	AMIR	7.00	6	420.16	0	1	6	12

109	Granular	0.000783	94.00	AMIR	6.40	6	475.38	0	1	6	12
110	Granular	0.0029	94.00	AMIR	6.30	6	485.46	0	1	6	12
111	Granular	0.004822	94.00	AMIR	5.80	6	562.95	0	1	6	12
112	Granular	0.004822	94.00	AMIR	5.80	6	723.42	0	1	6	12
113	Granular	0.0102	90.39	AMIR	5.00	8	79.68	0	0	3	7.5
114	Granular	0.00472	90.51	AMIR	5.00	8	137.88	0	0	3	7.5
115	Granular	0.00377	90.63	AMIR	5.00	8	169.65	0	0	3	7.5
116	Granular	0.00261	90.90	AMIR	5.00	8	186.95	0	0	3	7.5
117	Granular	0.00214	90.98	AMIR	5.00	8	188.62	0	0	3	7.5
118	Granular	0.0021	91.45	AMIR	5.00	8	312.92	0	0	3	7.5
119	Granular	0.00194	91.80	AMIR	5.00	8	318.22	0	0	3	7.5
120	Granular	0.00179	91.96	AMIR	5.00	8	340.35	0	0	3	7.5
121	Granular	0.00157	92.08	AMIR	5.00	8	389.03	0	0	3	7.5
122	Granular	0.000566	92.31	AMIR	5.00	8	408.2	0	0	3	7.5
123	Granular	0.000563	92.43	AMIR	5.00	8	426.18	0	0	3	7.5
124	Granular	0.00025	92.47	AMIR	5.00	8	434.56	0	0	3	7.5
125	Granular	0.000166	92.71	AMIR	5.00	8	534.25	0	0	3	7.5
126	Granular	0.000082	94.16	AMIR	5.00	8	551.8	0	0	3	7.5
127	Granular	0.000516	88.94	AMIR	5.00	8	373.28	0	2	7	15
128	Granular	0.00045	92.30	AMIR	5.00	8	235.96	0	2	7	15
129	Granular	0.000403	92.55	AMIR	5.00	8	509.84	0	2	7	15
130	Granular	0.000329	92.75	AMIR	5.00	8	525.49	0	2	7	15
131	Granular	0.000276	93.35	AMIR	5.00	8	501.21	0	2	7	15
132	Granular	0.000271	93.59	AMIR	5.00	8	241.18	0	2	7	15
133	Granular	0.000165	93.67	AMIR	5.00	8	252.54	0	2	7	15
134	Granular	0.000158	93.83	AMIR	5.00	8	174.93	0	2	7	15
135	Granular	0.000137	93.91	AMIR	5.00	8	408.19	0	2	7	15
136	Granular	0.000057	94.03	AMIR	5.00	8	203.42	0	2	7	15

137	Concrete	0.003123	88.40	AMIR	8.00	6	75.76	0	3	6	12.5
138	Concrete	0.002186	91.00	AMIR	8.00	6	95.39	0	3	6	12.5
139	Concrete	0.001754	92.00	AMIR	8.00	6	99.66	0	3	6	12.5
140	Concrete	0.001366	93.00	AMIR	8.00	6	100.31	0	3	6	12.5
141	Concrete	0.000718	93.00	AMIR	8.00	6	318.22	0	3	6	12.5
142	Concrete	0.000681	93.00	AMIR	8.00	6	330.74	0	3	6	12.5
143	Concrete	0.000563	93.00	AMIR	8.00	6	340.35	0	3	6	12.5
144	Concrete	0.02538	88.00	AMIR	9.00	8	76.82	0	0	0	0
145	Concrete	0.0253	88.40	AMIR	9.00	8	76.87	0	0	0	0
146	Concrete	0.0222	88.89	AMIR	9.00	8	95.62	0	0	0	0
147	Concrete	0.0154	90.06	AMIR	9.00	8	100.17	0	0	0	0
148	Concrete	0.01249	90.40	AMIR	9.00	8	112.88	0	0	0	0
149	Concrete	0.00725	92.24	AMIR	9.00	8	168.33	0	0	0	0
150	Concrete	0.00411	93.15	AMIR	9.00	8	299.39	0	0	0	0
151	Concrete	0.00669	90.00	AMIR	9.00	8	133.67	0	0	0	0
152	Concrete	0.00568	90.00	AMIR	9.00	8	213.86	0	0	0	0
153	Concrete	0.00338	91.00	AMIR	9.00	8	247.67	0	0	0	0
154	Concrete	0.00338	91.00	AMIR	9.00	8	285.57	0	0	0	0
155	Concrete	0.002336	92.00	AMIR	9.00	8	286.42	0	0	0	0
156	Concrete	0.001491	92.00	AMIR	9.00	8	312.92	0	0	0	0
157	Concrete	0.001115	92.00	AMIR	9.00	8	384.32	0	0	0	0
158	Concrete	0.01487	90.00	AMIR	8.00	8	285.04	0	0	4	11
159	Concrete	0.003398	91.00	AMIR	8.00	8	377.5	0	0	4	11
160	Concrete	0.003235	91.00	AMIR	8.00	8	490.13	0	0	4	11
161	Granular	0.002098	90.00	AMIR	5.00	8	300.23	0	0	2	11
162	Granular	0.001532	90.00	AMIR	5.00	8	315.14	0	0	2	11
163	Granular	0.001431	90.00	AMIR	5.00	8	330.74	0	0	2	11
164	Granular	0.00137	90.00	AMIR	5.00	8	345.27	0	0	2	11

165	Granular	0.00124	91.00	AMIR	5.00	8	373.28	0	0	2	11
166	Granular	0.000779	92.00	AMIR	5.00	8	377.09	0	0	2	11
167	Granular	0.000723	92.00	AMIR	4.00	8	377.5	0	0	2	11
168	Granular	0.000496	93.00	AMIR	4.00	8	509.84	0	0	2	11
169	Granular	0.000328	93.00	AMIR	4.00	8	525.49	0	0	2	11
170	Granular	0.00025	93.00	AMIR	4.00	8	726.01	0	0	2	11
171	Granular	0.000067	93.00	AMIR	4.00	8	755.53	0	0	2	11
172	Granular	0.000359	88.00	AMIR	6.50	6	230.22	0	1	6	11
173	Granular	0.00023	89.00	AMIR	5.80	6	361.37	0	1	6	11
174	Granular	0.00006	89.00	AMIR	5.70	6	475.38	0	1	6	11
175	Granular	0.000054	89.00	AMIR	5.60	4	485.46	0	1	6	11
176	Granular	0.000028	89.00	AMIR	5.60	6	544.99	0	1	6	11
177	Granular	0.000023	90.00	AMIR	5.60	8	554.99	0	1	6	11
178	Granular	0.000022	90.00	AMIR	5.60	4	562.95	0	1	6	11
179	Granular	0.000021	90.00	AMIR	5.50	8	624.15	0	1	6	11
180	Granular	0.000011	91.00	AMIR	5.50	8	723.42	0	1	6	11

Appendix 2 Descriptive statistics of percent compaction in common trial locations

Location / compaction method	Sample size	Minimum	Maximum	Range	Standard deviation	Variance	Mean
Inhouse 2012							
AMIR	10	92.47	97.73	5.26	1.79	3.21	95.16
CCM	10	90.47	94.12	3.65	1.26	1.59	92.77
Highway 28							
AMIR	10	86.94	94.16	7.22	1.94	3.75	91.64
CCM	10	87.73	91.8	4.07	1.24	1.54	90.58
Highway 2 S							
AMIR	10	92.30	94.13	1.83	0.62	0.38	93.40
CCM	10	92.01	94.11	2.1	0.71	0.51	93.27
Local Rd							
AMIR	6	89.90	93.00	3.1	1.38	1.92	91.54
CCM	6	88.25	93.81	5.56	1.95	3.81	90.44
Inhouse 2016							
AMIR	15	89.20	93.48	4.28	1.34	1.80	90.65
CCM	15	88.00	94.53	6.53	1.94	3.77	91.31
Highway 401							
AMIR	10	89.54	93.61	4.07	1.25	1.57	90.94
CCM	10	86.89	89.61	2.72	1.01	1.01	88.45
Highway 520							
AMIR	10	89.23	92.24	3.01	1.11	1.23	90.89
CCM	10	89.07	91.32	2.25	0.78	0.61	90.35
Highway 7							
AMIR	10	87.75	96.00	8.25	2.36	5.57	90.10
CCM	10	89.07	91.18	2.11	0.85	0.72	90.30

Appendix 3 Descriptive statistics of permeability in common trial locations

Location / compaction method	Sample size	Minimum x10^-3 cm/sec	Maximum x10^-3 cm/sec	Range	Standard deviation	Variance	Mean
Inhouse 2012							
AMIR	25	0.01	13.52	13.51	3.60	12.98	2.81
CCM	25	0.11	17.52	17.41	5.00	25.03	6.30
Highway 28							
AMIR	9	0.08	3.77	3.69	1.19	1.42	1.07
CCM	15	0.44	7.48	7.04	2.58	6.65	3.24
Highway 2 S							
AMIR	10	0.06	0.52	0.46	0.15	0.02	0.28
CCM	10	.05	0.74	0.69	0.23	0.05	0.32
Local Rd							
AMIR	11	0.07	2.10	2.03	.64	0.41	0.94
CCM	7	0.49	9.06	8.57	3.68	13.53	3.77
Inhouse 2016							
AMIR	13	0.43	5.84	5.41	1.84	3.38	2.89
CCM	15	0.12	51.12	51	16.85	283.95	18.16
Highway 401							
AMIR	7	0.19	25.34	25.15	9.28	86.18	12.42
CCM	5	19.34	45.32	25.98	12.03	144.80	32.31
Highway 520							
AMIR	7	1.12	6.69	5.57	2.08	4.33	3.44
CCM	6	5.16	24.35	19.19	7.19	51.71	11.85
Highway 34							
AMIR	7	0.56	3.12	2.56	0.94	0.89	1.48
CCM	7	3.32	6.23	2.91	1.07	1.15	4.87
Highway 7							
AMIR	15	3.07	19.77	16.7	4.97	24.72	7.08
CCM	5	0.24	6.60	6.36	2.32	5.39	2.87

Appendix 4 Poor compaction in core sample hole