Pothole Condition in Canada and Evaluation of Maintenance Material

by

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ABSTRACT

Potholes are one of the most concerning deteriorations of asphalt pavement in cold climatic regions. Repair of potholes is an important form of maintenance operations for asphalt pavements conducted by most of the transportation agencies. Although a large number of previous researches including field monitoring, laboratory testing and questionnaire survey were conducted for the past three decades to study pothole repair in specific parts of the United State and Europe, limited research efforts have been devoted to inspect the severity of the pothole problem and its maintenance practice in Canada. Therefore, this research work attempts to investigate pothole severity, conduct critical assessment of current maintenance practices and identify resources available for pothole repair throughout Canada. In order to attain the main objective of this study, a questionnaire was prepared and distributed to Canadian transportation agencies. According to the survey outcomes from six provinces (Alberta, Manitoba, Ontario, Quebec, Saskatchewan and New Brunswick), a greater percentage of moderate to high severe potholes was noticed in the study area. Freeze-thaw cycle was identified as the most influential factor in pothole formation, and a large portion of pothole repairs was typically performed in the summer period. Moreover, the study results identified the most frequently used patching materials and methods in these provinces and patch durability. Inadequate stability, adhesion, cohesion and stripping potential of patching materials and improper compaction during patching operations were determined to be the main reasons of patch failure based on the concerning distresses of the repaired patch. To evaluate the performance of patching material, a laboratory testing program was conducted on cold mixes that were identified as being most frequently used by the survey. The laboratory results showed that curing time and temperature had a significant effect on strength gain for all cold mixes. Substantial freeze-thaw damage potential was also noticed for the cold patching materials.

PREFACE

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Dedicated to my parents and husband

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Chapter 1. Introduction

1.1. Background

Pavement maintenance for potholes is currently an important issue, especially in cold region areas where adverse weather conditions significantly contribute to the development and acceleration of the pothole problem. Deterioration of pavement is generally defined as a process of distress development due to the combined effects of pavement materials, subgrade soil condition, traffic loading and environmental factors. Asphalt pavement surface distresses are categorized into four types of deteriorations named as cracking, surface deformation, surface defects and disintegration. One of the most concerning pavement disintegrations in cold weather regions, potholes, is the main focus of this thesis. Potholes are bowl-shaped depressions of varying sizes that penetrate all the way through the surface layer down to the base course, frequently encountered on the surface of flexible pavements (Miller and Bellinger 2003). Formation of potholes not only decreases the service life of pavement but also significantly reduces the performance level of roads. It can begin from more severe interconnected alligator and longitudinal cracks and raveling of pavement surface. Additionally, water penetrating into the top layer of asphalt through the cracks also causes the development of potholes. Freeze-thaw cycles accelerate the process of pothole formation; late winter and early spring are considered as the freezing and thawing period, respectively (Maher *et al.* 2001). Material and thickness of pavement structure, traffic loading, inappropriate repair of pavement distresses, pavement age, rate of precipitation and winter maintenance are also responsible for acceleration of pothole development (Paige-Green *et al.* 2010).

Pothole patching is a well-known asphalt pavement maintenance operation in cold climatic regions. The two main components of pothole repair operations are patching mixtures and methods (Wilson and Romine 2001). The widely used patching materials in the United States and Canada are proprietary cold mixes produced with emulsified or cutback bitumen to increase workability in cold weather and antistripping agents to reduce moisture susceptibility (Prowell and Franklin 1996). Hot mixed asphalt (HMA) produces a more durable and longer lasting patch than the cold mixes. Potholes are filled following different procedures in different seasons. The ‘throw-and-go’ is the simplest and most widely used patching method. The repair procedure includes placing material into the pothole, compacting it using truck tires and leaving a 3 to 6 mm crown above the pothole. Patching a pothole takes a few minutes using this method. For this reason, this method is suitable for temporary pothole repair in winter periods with adverse weather conditions. The semi-permanent technique is popular for permanent repair in the summer. The patching procedure in a semi-permanent method includes removing water and debris from the pothole, straightening the edges, placing the mixture and compacting it with specific devices. Normally, the time taken to repair a pothole using this method is greater than that of the ‘throw-and-go’ method. Thus, patching potholes using this method in the winter season creates difficulties. Other than these two methods, spray injection and edge-seal patching methods are also used for pothole repair. Similar to ‘throw-and-go’, spray injection repair technique requires a few minutes and less labour for the patching operation. Consequently, this method can be also considered appropriate for winter season patching. However, performance and durability of the repaired patch largely depends on the patching mixture and method used to fill the pothole. Pavement is exposed to low temperatures during winter periods, and freeze occurrence is common at that time. Moreover, thaw is very frequent in spring. Thus, a winter-laid patch receives immediate stress from freeze and has a shorter survival period than the summer patch (Wilson and Romine 2001). Pothole repair strategies can be also evaluated by monitoring the post-patching distresses. The frequently noticed patch distresses are alligator cracking, bleeding, edge disintegration, missing patch, shoving, raveling and dishing. The post-patching distresses are results of inadequate stability, adhesion, cohesion and strength in the patching mixture. Improper mixture design is also responsible for some developed distresses. Sometimes inadequate compaction during repair work also causes distresses in the repaired patch. Moreover, usage of tack coat into the sides and bottom of the pothole prior to placing the patching material increases adhesion of the mixture with the existing pavement surface and thus creates a durable patch (Prowell and Franklin 1996). However, selecting the perfect combination of pothole repair method and material considering the weather conditions is the key to a durable patch.

Significant research efforts have been devoted to pothole maintenance during the last three decades. The very first attempt to study the pothole repair operation and discover the most economic procedure was taken by Thomas and Anderson in 1986. Extensive work was carried out through the Strategic Highway Research Program (SHRP) H-106 project in order to investigate the performance of different materials, procedures and equipment for pothole repair. As part of this project, more than 1,200 patches were placed using proprietary, state-specified, and local cold-mix patching materials and several installation techniques. The sites were located across the United States and Canada under four climatic regions: wet-freeze, dry-freeze, wet-nonfreeze and dry-nonfreeze (Wilson and Romine 1993, 1994, 2001). Several long-term field monitoring and laboratory studies were performed to determine the effectiveness of pothole repair methods and cold patching materials (Prowell and Franklin 1996, Maher *et al.* 2001, Dong *et al.* 2014a, b, Dong *et al.* 2015). In addition, a number of questionnaire surveys were also conducted in two different regions of the United States and Europe to determine the widely used pothole patching mixtures, methods and equipment utilized by local transportation agencies (Griffith 1998, Dong *et al.* 2014c, Nicholls *et al.* 2014). However, Canada is located in cold climatic regions, and the pothole is the most serious asphalt pavement distress in this area that is not only expensive for maintenance but also creates hazardous conditions for road users. Every year, almost 658 pothole damage claims are recorded by the City of Edmonton, and approximately half a million dollars is required to pay out these vehicle damage claims (City of Edmonton). As a result, it is critical to investigate pothole maintenance in Canada in order to study the severity of this problem, factors responsible for the development of potholes, and current maintenance practices in different provinces and their effectiveness.

1.2. Problem statement

Canada is situated in cold regions with an extreme winter climate. Canadian provinces are under dry-freeze and wet-freeze regions. Among them, Alberta, Manitoba, Ontario, Quebec and Saskatchewan are under a high-freeze climatic zone. The extreme climatic condition causes harmful impacts on pavement structures that result in deterioration. Potholes are one of the most concerning and severe issues throughout the cold regions of this country. Due to the extreme drop in air temperature during winter, heave occurs to the ground underneath the pavement structure that affects the cracking of the asphalt surface. After a certain rise in temperature, the cracks are filled by the melted snow that freezes and expands again after a decrease in temperature. This expansion causes material loss after traffic loading over the area and thus creates potholes. On average, approximately 122 freeze-thaw cycles occur in Edmonton every year. This number has been increasing up to 165 for the last five years, and that results in more pothole generation around this city (Mertz 2015, Lazzarino 2015). As well, numerous other factors directly or indirectly relate to the acceleration of pothole formation. In Edmonton, some of the pavements are in extremely old condition. Because of the aged structure, pavement cracks occur in addition to the asphalt surface wearing down due to oxidation and traffic loading (Hixson 2015). Thus, it becomes essential to investigate the climatic data and present conditions of road networks around the cold regions of Canada, establish the factors responsible for pothole generation in different provinces, and study the severity of the pothole problem.

Pothole patching is an important form of maintenance operations for asphalt pavements conducted by most transportation agencies. On average, 400,000 potholes are filled in Edmonton every year, and the average annual budget for pothole patching is approximately three million dollars (Male 2013). In 2015, the annual pothole repair budget was approximately 5.9 million dollars, which is almost twice the average yearly budget (City of Edmonton 2015, CBC 2015). Hence, it is necessary to determine the current practices of pothole maintenance and measure their effectiveness through the durability of repaired patch and post-patching distresses. As part of this research, a questionnaire was developed and distributed to the provincial transportation agencies of Canada. The results and findings of the survey were analyzed to attain the main objective of this study. In addition, the most frequently used patching materials were identified from the survey results and tested in the laboratory for quality assurance.

1.3. Objectives

The major objectives of this research are listed below:

1. Literature review of past research efforts on flexible pavement pothole repair techniques and patching material evaluation.
2. Investigating the severity of the pothole problem throughout Canada.
3. Establishing the factors responsible for pothole development.
4. Identifying current practices of pothole patching in different regions in Canada.
5. Studying the performances of different combinations of patching techniques based on survival periods and post-patching distresses.
6. Studying laboratory performance of the used patching materials according to survey results.

1.4. Methodology

To investigate current pothole maintenance in Canada, a questionnaire was developed based on pavement maintenance for potholes in cold climate regions. The questionnaire was sent to Canadian provincial transportation agencies in September 2014. The questionnaire gathered information on the network characteristics; causes of pothole development; pothole repair strategy combining repair season, patching material and method; efficiency of various repair techniques; pavement repair budget; and suggestions on future developments in pothole repair. According to the survey results from six provincial agencies in Canada (Alberta, Manitoba, Ontario, Quebec, Saskatchewan and New Brunswick), the used patching materials were tested in the laboratory to evaluate performance. The laboratory testing program includes Marshall Stability, adhesiveness, cohesion and indirect tensile strength tests.

1.5. Organization of the thesis

The thesis is presented in the following organization:

In Chapter 1, a brief introduction to the asphalt pavement maintenance for potholes is given and the motivation of the research is highlighted.

In Chapter 2, a review of flexible pavement distresses, definition and types of potholes, factors responsible for pothole formation, patching materials and procedures, and causes of repaired patch failure are described briefly. In addition, the previous research in this field is also discussed.

In Chapter 3, the result of a questionnaire survey on pavement maintenance for potholes in cold climate regions from six provincial transportation agencies in Canada is presented. Based on the survey outcome, the severity of the pothole problem, causes of pothole development, current repair practices and their performances in Canada were investigated.

In Chapter 4, pothole repair practices in six provinces of Canada were studied based on questionnaire results and the performances of the used patching materials according to survey results were investigated through laboratory testing.

In Chapter 5, the approaches of the research are summarized, findings of the studies are highlighted and further topics are proposed for future research.

Chapter 2. Literature Review

2.1. Flexible pavement distresses

Flexible pavement is subjected to distresses and deformations due to a group of factors including traffic loading, environment conditions, construction quality, maintenance operation and aging. In this section, flexible pavement distresses of different classes are discussed briefly and a subset of interest is defined. Flexible pavement deterioration is divided into five categories as below (Miller and Bellinger 2003, Adlinge and Gupta 2013).

Cracking

Repeated traffic loading is the main cause of crack development. Cracks are classified into different types named as fatigue, block, edge, longitudinal, reflection and transverse, depending on the shape of the cracks and the location of crack development.

Patching and potholes

When a portion of pavement surface is removed and replaced with addition material applied to the pavement after original construction, it is called patch deterioration. Potholes, on the other hand, are bowl-shaped holes in the pavement surface with various dimensions.

Surface deformation

Two specific types of surface deformation are rutting and shoving. Rutting is a longitudinal surface depression caused by traffic loading. Shoving is longitudinal and vertical displacement of a localized area of the pavement surface, caused by braking or accelerating vehicles. It is usually located at intersections or on hills or curves.

Surface defects

The most common surface defects are bleeding, polished aggregate and raveling. Bleeding generally occurs in the wheel paths. It can be defined as the presence of excess bituminous binder on the surface of pavement. Polished aggregate is the condition of a pavement when the surface binder is worn away and the coarse aggregate are exposed. Raveling is the wearing away of the pavement surface caused by the dislodging of aggregate particles and loss of asphalt binder. It ranges from loss of fine aggregate to loss of some coarse aggregate and ultimately to a very rough and pitted surface with obvious loss of aggregate.

Miscellaneous distresses

Lane-to-shoulder dropoff and water bleeding and pumping are two types of miscellaneous distresses. When there is an elevation difference between the pavement surface and the outside shoulder, it is called lane-to-shoulder dropoff. The main reason for this distress is the settlement of shoulder due to pavement layer material differences. Water bleeding and pumping of fine material occurs from beneath the pavement through cracks.

2.2. Definition and types of potholes

Potholes can be defined as bowl-shaped depressions of varying sizes that penetrate all the way through the surface layer down to the base course, frequently encountered on the surface of flexible pavements. It is one of the most common deteriorations of asphalt pavement, occurring mainly in cold weather regions.

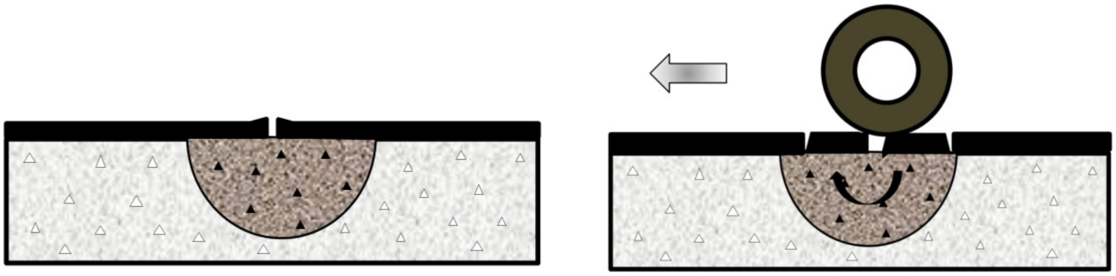
Potholes are classified into different severity categories depending on the depth of the hole. A pothole less than 25 mm deep is in the low severity category. A pothole 25 mm to 50 mm deep is in the moderate severity category. Finally, a pothole more than 50 mm deep is in the high severe category. Figure 2-1 represents potholes in different categories of severity (Miller and Bellinger 2003).

(a) Low severity pothole (b) Moderate severity pothole (c) High severity pothole

Figure 2-1: Potholes in different severity categories (Miller and Bellinger 2003)

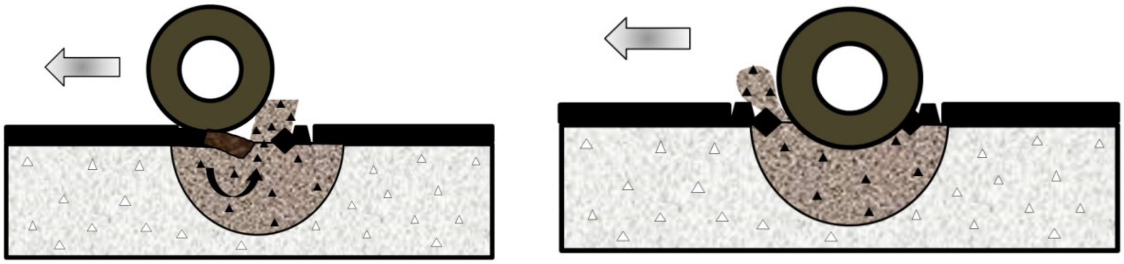
2.3. Formation of potholes

In flexible pavements, pothole formation begins in the weakened areas. Usually, a more severe interconnected alligator crack in pavement surface turns into a pothole when it is broken down and pulled up by the heavy loads of travelling vehicles. In addition to fatigue cracks, potholes can also be initiated from longitudinal cracks of high severity and raveling of pavement surface (Dong *et al.* 2014a, Dore and Zubeck 2009). Structural response of flexible pavement is largely influenced by the variation of pavement temperature. Daily and seasonal fluctuation of temperature causes expansion and contraction of pavement material that result in the generation of thermal strain. Thermal cracking is the result of thermal induced stress. It is one of the most serious distresses in flexible pavement, especially in regions where daily and seasonal temperature change is significant and rapid (Tarefder and Islam 2014). Laboratory test results of asphalt strain generation in winter and fall season is presented in Appendix B. Potholes are generated due to water penetrating into the top layer of asphalt through the cracks. In cold regions, when water penetrates into the asphalt layer, it freezes and increases about nine percent in volume, which makes the cracks larger in size (Barbaccia 2009). This process is accelerated by freeze-thaw cycles. Freezing leads to water expanding inside the pavement layer and creating additional tensile stresses that can result in further breakdown of pavement surface. Moreover, freeze and thaw cycles develop voids in the subgrade that can lead to formation of potholes upon traffic loading (Maher *et al.* 2001). Figure 2-2 represents the typical procedure of pothole development. Normally, the late winter and early spring is considered the freezing and thawing period of the year.



(a) Creation of sensitive saturation zone near cracks

(b) Hydrostatic pressure induced in sensitive saturated zone by moving wheel load



(c) Removal of broken pieces of asphalt concrete

(d) Active erosion of pavement material caused by tire pressure

Figure 2-2: Development of a pothole

Apart from that, formation of potholes depends on other factors such as material and thickness of pavement structure, traffic loading, inappropriate repair, pavement age, high precipitation rate and winter maintenance. These factors are discussed below (Paige-Green *et al.* 2010).

1. **Material and thickness of pavement structure:** For asphalt concrete pavement structure, pothole formation initiates from the asphalt surface cracking and water penetrating through the cracks to the layer underneath. Pavement surface may crack due to poor support, unsuitable material or thickness of layers. High surface deflection under traffic loading is a result of a weak underlying base layer that may create cracks on the asphalt surface. Rapid pothole development is the result of further trafficking or water penetration through the cracks into the base layer. Moreover, moisture build-up beneath the asphalt layer as a result of poor drainage systems may also create potholes.

2. **Traffic loading:** When the traffic loading exceeds the pavement design loading, it may lead to excessive road deflection that results in surface cracks of the pavement structure. These cracks allow water to penetrate into the layer underneath and cause material loss, which creates potholes.

3. **Inappropriate repair:** Improper repair of pavement distresses cause rapid failure of the distressed area and creates further disintegration. In the case of pothole repair, proper patching materials and methods should be used to confirm the highest durability of patch, even when patching is done as a temporary measure. However, late rehabilitation of distresses such as cracking and raveling may create more severe distresses or generate potholes.

4. **Pavement age:** Bituminous pavement surface is subjected to the development of cracks over time due to oxidation and drying of binder material. However, routine preventative maintenance can be a remedial measure for this issue.

5. **High precipitation rate:** Although a high precipitation rate is not directly associated with pothole formation, it accelerates the process of pothole development because the majority of potholes are associated with wet conditions.

6. **Winter maintenance:** For cold regions, winter maintenance practice, especially snow removal policy, indirectly affects the process of pothole generation. Snow removal policy includes frequency and location of snow removal, usage of sand, salt or anti-icing agents, and road priority basis removal. Roadside storage of snow causes wet conditions after melting that may penetrate through cracks and create potholes.

2.4. Pothole repair

Pothole patching is one of the important forms of maintenance operations for asphalt pavements. The basic requirement for the scope of pothole repair according to the Strategic Highway Research Program (SHRP) is that a pothole developed in flexible pavement with a size limit of 25 mm to 150 mm (0.09 to 0.93 m^2) closely or infrequently spaced should be repaired in any weather condition (Blaha 1993). Patching of potholes is performed under various weather conditions and temperature cycles. The quality of the pothole patching operation depends on the choice of patching material as well as the repair procedure. Various combinations of patching materials and repair techniques can be used in different seasons. Pothole patching seasons, materials and procedures are described below.

2.4.1. Pothole patching seasons

Pothole patching season is usually divided into two periods for cold regions: winter and summer. In winter, pavement is exposed to low temperatures and freeze occurrence is common during that period. As a result, the winter-laid patch receives immediate stress from freeze and has a shorter survival period than the summer patch. Pothole patching during this time is performed as an emergency repair with cold patching mixtures because most of the hot mixes are not workable during the cold weather conditions. On the other hand, wet and soft base material is used in the spring period due to frequent thaw. Most of the pothole patching operation is performed in the summer period when the weather conditions are warmer and drier (Wilson and Romine 2001).

2.4.2. Pothole patching materials

Bituminous patching mixture is a combination of binder and aggregates that have a special characteristic for filling potholes in affected pavements. In general, patching materials are classified into three different categories based on the type of mixing and the temperature of the mixture at the time of placement. The first type is the hot-mixed and hot-placed patching mixture. This type of asphalt concrete patching mixture is produced in plants and applied right after production. The second type is the hot-mixed and cold-placed mixture. The main difference between these two types of mixtures is that cold-placed mixture is used cold from the stockpile and thus should be workable under all weather conditions. The third type is the cold-mixed and cold-placed mixture (Maher *et al.* 2001) that is widely used for pothole patching in cold regions, particularly in winter time, when most of the potholes develop. Cold mixes are produced with emulsified or cutback asphalt to increase workability in cold weather and antistripping agents to reduce moisture susceptibility.

High quality material is one of the most important parameters for a durable patch (Kuennen 2004). Bituminous patching materials should have some special and important properties to make a longer lasting patch. The most important properties are described below.

Stability: Stability is one of the critical properties of the mixture that helps to resist vertical and horizontal deformations of the patch caused by traffic loads. Stability is related to the material characteristics of the patching mixture and can be increased by using good graded, angular aggregate with rough surface texture (Maher *et al.* 2001, Chatterjee *et al.* 2006, Pimentel 2007).

Workability: Temperature is the most important factor in regulating the workability of a mixture as it controls the viscosity of bituminous binder. The workability of a patching mixture can be increased by using a soft binder with additives and open graded and rounded aggregates with fewer fines. A less workable patching mixture provides inadequate compaction during placement of the material and causes poor performance of the patch. On the other hand, a mixture with more workability is less stable and sometimes causes shoving under vehicular loading (Rosales *et al.* 2007, Pimentel 2007).

Durability: A patching mixture is called a durable mixture when the patch has satisfactory resistance to disintegration. Normally, hot-mix hot-placed bituminous materials are more durable than others (Maher *et al.* 2001, Pimentel 2007).

Skid resistance: Skid resistance is the frictional resistance offered by the surface of the patch. This property should be similar to the pavement in which the patch is placed. Patching mixture containing an excessive amount of asphalt binder or aggregate that can be easily polished may cause poor skid resistance (Maher *et al.* 2001, Chatterjee *et al.* 2006, Pimentel 2007).

Stickiness: A good quality patch should have stickiness (adhesion and cohesion properties) so that it adheres to the underlying pavement and sides of the pothole and preserve its own integrity. Stickiness is highly influenced by the amount and type of binder and the temperature of the patching mixture. Consequently, hot-mix patching material has proven to exhibit stickier characteristics compared to cold patching materials (Maher *et al.* 2001, Chatterjee *et al.* 2006, Pimentel 2007).

Stripping resistance: The separation of asphalt binder from aggregate in the presence of water is referred to as stripping. Resistance to water action is an important property of patching material to keep the binder from stripping off the aggregate. Types of binder and aggregate largely affect this property of a mixture. Due to poor water drainage systems, the stripping potential of a water-susceptible mixture can be significant for a repaired pothole (Maher *et al.* 2001, Chatterjee *et al.* 2006, Pimentel 2007).

Storage ability: This is an important property, especially for stockpiled mixtures that should remain workable for a desired period of time, normally six to twelve months. When loss of volatiles occurs rapidly because a mixture contains improper liquid asphalt binder, it becomes harder with time and difficult to stockpile for a certain time period. A patching material without storage ability properties could face its binder draining off and thus will not be usable for future repairs. Covering mixtures with tarps or polyethylene may extend the time of storage (Maher *et al.* 2001, Chatterjee *et al.* 2006, Pimentel 2007).

In most cases, cold patching materials are stockpiled for future usage. Maintaining good workability and durability are two major challenges for a stockpile patching material that depends largely on the properties of a mixture. Table 2-1 shows the patching mixture characteristics for different parameters of material properties (Marcus and Elizabeth 2001). This table certifies that a mixture consisting of open graded, round and finer aggregate with low viscous binder has good workability but less durability. On the other hand, mixtures consisting of dense graded, angular and finer aggregate with high viscous binder have good durability but poor workability.

Table 2-1: Pothole patching mixture characteristics for different parameters of material properties (Marcus and Elizabeth 2001)

Property	Parameter	Workability	Durability
Gradation	Open gradation	Good	Poor

	Dense gradation	Poor	Good
	One size	Good	Poor
Aggregate shape	Angular	Poor	Good
	Round	Good	Poor
Aggregate size	Larger gradation	Poor	Good
	Finer mix	Good	Good if depth <76mm
Binder viscosity	Low viscosity	Good	Poor
	High viscosity	Poor	Good
Antistrip			Good if compatible

A great variety of cold patching materials are being used for pothole repair in different parts of Canada and the USA. Among them, the most popular patching materials are hot mixed asphalt (HMA), conventional cold mix (CCM), quality pavement repair (QPR), unique paving material (UPM), innovative asphalt repair (IAR), EZ Street, Performix, SuitKote, Permapatch, WesPro, spray injection material and local materials. Descriptions of the materials are as follows.

HMA: Hot mixed asphalt (HMA) material is a combination of approximately 95% aggregate and 5% asphalt binder by weight of HMA mixture. This mixture contains 85% aggregate, 10% asphalt binder and 5% air void by volume of HMA mixture. High quality crushed stone or gravel is used as aggregate in preparing the HMA mixture. The asphalt binder is heated and mixed in measured quantities to produce the HMA mixture. Fibers, crumb rubber and anti-strip additives are sometimes added to the HMA mixture to enhance its workability (NCHRP 2011).

CCM: CCM is a category of cold applied pavement repair materials. This mixture consists of dense graded aggregate and is normally used for temporarily fixing potholes (Lavorato *et al.* 2013).

QPR: QPR is a cold-mix proprietary material that consists of 100% crushed granular aggregates with an open gradation and modified bituminous liquid blend. Specific gravity of the aggregates is measured as 2.55% to 2.75%. The mixture contains 4.0% to 6.0%

bitumen by weight of mixed material. Aggregate coating with bitumen is 95% and this material remains cohesive up to -26°C (QPR Material Specification).

UPM: UPM is a high performance cold patching material. UPM contains 5.0% to 6.5% specially formulated binder and 95% to 93.5% aggregate. Before mixing, the asphalt is heated to a temperature between 88°C and 135°C. After heating, the asphalt is mixed with cold aggregate in a pug mill for 30 to 45 seconds. ASTM requirements are used for selecting binder and aggregate. ASTM requirements for aggregate is ASTM C-136 (Maher *et al.* 2001, Wilson and Romine 1993).

IAR: IAR consists of cutback bitumen and granular aggregates with a minimum 80% crushed particles. The mixture contains 4.5% to 6.0% cutback bitumen by weight of mixed material. This material can be used at temperatures below 0°C, remaining flexible and cohesive up to -10°C (ProPatch Specification Sheet).

EZ Street: EZ Street consists of polymer modified cold asphalt mixed with open graded aggregate. It can be used in the presence of water and all weather conditions. EZ Street is workable between -18°C and 38°C air temperature. In the winter period, this material can be heated up to a material temperature of 50°C using a hot-box before application. This material can be stored for reuse (EZ-Street asphalt).

SuitKote: SuitKote is a proprietary cold mixture consisting of crushed aggregate and bituminous material. ASTM requirements are used for selecting binder and aggregate. For mixing the aggregate with the binder, batch mix plant, drum mix plant or a cold-mix pug mill are used. Temperature is minimized during mixing to avoid the stripping potential of bituminous material (Maher *et al.* 2001).

Permapatch: Permapatch is a proprietary material containing a specially formulated binder and local aggregate. Normally limestones are used as aggregate for preparing Permapatch. Weight of bituminous material is 5.0% to 6% based on the total weight of mixture (Maher *et al.* 2001, Wilson and Romine 1993).

WesPro: WesPro is a proprietary cold mixture consisting of aggregate and liquid blend. Limestone is used as aggregate and it should follow a standard of ASTM C-136 (Maher *et al.* 2001).

Spray injection materials: Spray injection materials consisting of crushed aggregate and emulsified asphalt are used to repair potholes quickly and permanently. A spray injection device is used for placement of this material. Before placement, the emulsion is heated at around 60°C (Maher *et al.* 2001, Wilson and Romine 1993).

Local material: The most inexpensive material is the local material that contains rounded aggregate and a small percentage of binder (Maher *et al.* 2001, Wilson and Romine 1993).

2.4.3. Pothole patching techniques

A number of patching techniques are available for pothole repair. The most common repair methods are: (a) throw-and-go, (b) semi-permanent, (c) spray injection, and (d) edge-seal. All these methods are identical depending on the repair procedure and equipment needed for the repair operation. The repair procedures of these methods are described below (Maher *et al.* 2001, Wilson and Romine 2001, Maupin *et al.* 2003).

(a) Throw-and-go: The most widely used patching method is 'throw-and-go', also known as 'throw-and-roll' method. It is a very simple and quick patching technique that manifests the highest production rate among all the reviewed methods. Repairing procedure consists of the following steps: placing the material into the pothole, compacting the material using truck tires, and verifying the crown of the compacted patch between 3 and 6 mm. Most often, the 'throw-and-go' method is used for temporary repairs in winter time. Figure 2-3 shows the pothole repair procedure of the 'throw-and-go' method (Maher *et al.* 2001, Wilson and Romine 2001).

(i) Placing material into pothole

(ii) Compacting using truck tires

Figure 2-3: Pothole repair procedure of throw-and-go method (Wilson and Romine 2001)

(b) Semi-permanent: The semi-permanent repair technique is popular for permanent pothole repairs in summer time. In this method, the water and debris are cleaned from the pothole before placing the patching material. After cleaning, the sides of the potholes are squared up to make a sound pavement. Then the materials are placed and compacted with a device smaller than the patch area. Single-drum vibratory rollers and vibratory plate compactors are normally used for compaction. Figure 2-4 shows the pothole repair procedure of the semi-permanent method (Maher *et al.* 2001, Wilson and Romine 2001).

(i) Pothole edges are straightened up

(ii) Compaction of patching material

Figure 2-4: Pothole repair procedure of semi-permanent method (Wilson and Romine 2001)

(c) Spray injection: Spray injection is another highly productive method as it requires only a few minutes to complete a pothole repair. This method consists of the following steps: blowing water and debris from the pothole, spraying a tack coat of binder on the sides and bottom of the pothole, blowing asphalt and aggregate into the pothole, and covering the patch area with a layer of aggregate. In this method, compaction is not required after placing the cover aggregate. Two types of spray injection devices are available: (i) truck and trailer unit, and (ii) self-contained unit. Figure 2-5 shows the spray injection patching procedure and devices available for pothole repair (Maher *et al.* 2001, Wilson and Romine 2001, Maupin *et al.* 2003).

(i) Blowing water and debris from the pothole

(ii) Blowing asphalt and aggregate into pothole

(iii) Covering patch with dry aggregate

(iv) Truck and trailer unit (v) Self-contained unit

Figure 2-5: Spray injection patching procedure and devices available for pothole repair (Maupin *et al.* 2003, Wilson and Romine 2001)

(d) Edge-seal: The procedure of the edge seal method is quite similar to the 'throw-and-go' method. Initially, the material is placed into the pothole without any prior preparation or removal of water or debris. The second step includes compacting the material using truck tires and verifying the crown of the compacted patch is between 3 and 6 mm. When the repaired section dries, a layer of asphaltic tack material and a layer of sand are placed on top of the patch to prevent tracking by vehicle tires (Maher *et al.* 2001, Wilson and Romine 2001).

2.5. Causes of repaired patch failure

Performance of pothole repair strategies can be measured by the durability of patch and post-patching distresses. Several studies have been conducted to evaluate the performance of different combinations of patching materials and methods. During the evaluation of a repaired patch, a number of distresses were identified as the causes of its failure. The most commonly reported patch distresses are alligator cracking, bleeding, edge disintegration, missing patch, shoving, raveling and dishing. These distresses are described below (Prowell and Franklin 1996, Dong *et al.* 2014a, Maher *et al.* 2001, Lavorato *et al.* 2013).

Alligator cracking: Alligator cracking is a typical pothole patch distress during winter caused by freeze-thaw cycles. Due to improper adhesion of the patch to the hole, freeze-thaw damage occurs. It produces delamination of the patch from the original pavement as a result of freezing water at the bottom of the repair. Figure 2-6 (a) represents a typical phenomenon of cracking distress on a repaired patch (Dong *et al.* 2014a, Maher *et al.* 2001).

Bleeding: This kind of distress refers to the flushing of asphalt binder onto the patch surface. Bleeding is caused by a combination of traffic load, inadequate voids and excessive binder in the mixture. This distress can be controlled with an appropriate mixture design. Bleeding pavement surface causes poor skid resistance. A common overview of bleeding distress on a repaired patch is shown in Figure 2-6 (b) (Dong *et al.* 2014a, Maher *et al.* 2001, Lavorato *et al.* 2013).

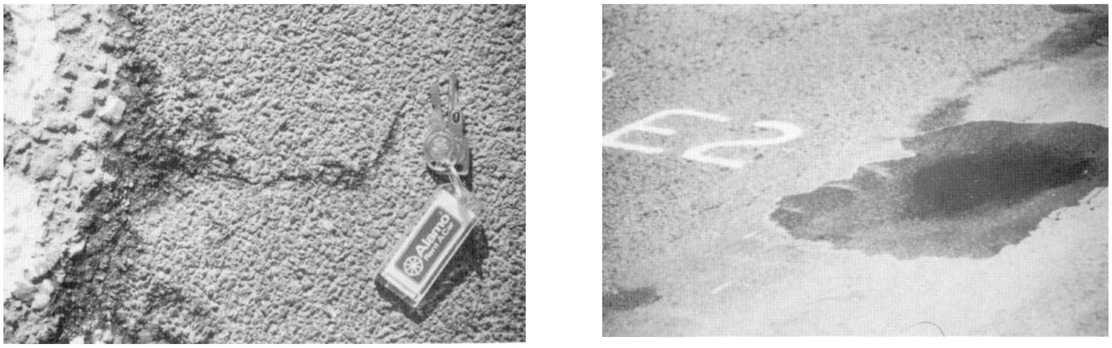
Edge disintegration: Edge disintegration is another mode of failure that occurs when the patching materials lose adhesion to the sides of the pothole. Figure 2-6 (c) shows the edge disintegration distress on a repaired patch (Lavorato *et al.* 2013).

Missing patch: A missing patch is the loss of patching materials due to lack of adhesion, cohesion, alligator cracking and insufficient compaction (Dong *et al.* 2014a, Lavorato *et al.* 2013).

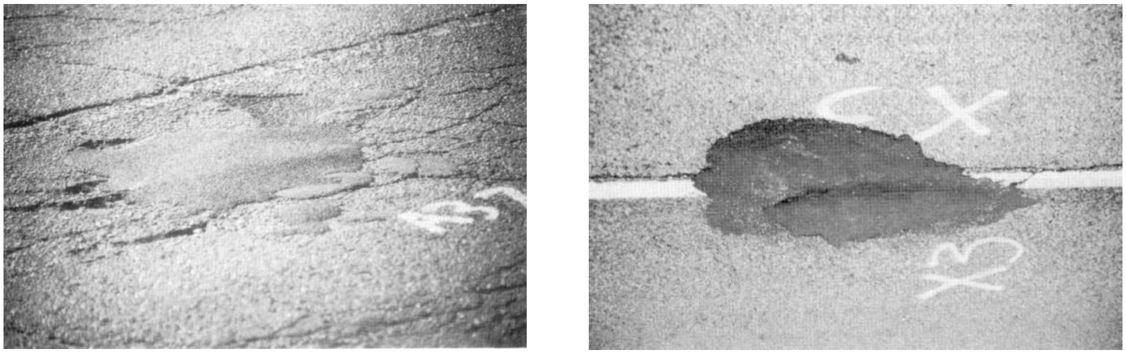
Shoving: Shoving is the vertical or horizontal movement of a patch. When various factors cause a patching material to lose stability, shoving occurs under traffic loading. The most important factor to attain stability is proper compaction during the patching operation. Proper compaction confirms sufficient aggregate interlock that is responsible for the stability of the patching material. A patch becomes more susceptible to shoving due to inadequate compaction. Figure 2-6 (d) represents a typical phenomenon of shoving distress on a repaired patch (Maher *et al.* 2001, Prowell and Franklin 1996, Lavorato *et al.* 2013).

Raveling: Raveling is the progressive loss of aggregate from the surface of the patch. It is caused by stripping, poor cohesion due to inadequate compaction during patching operation, and presence of excessive fines in patching mixture. Stripping is the loss of asphalt coating of the aggregates due to moisture infiltration that can lead to gradual disintegration of the patch. Raveling distress on a repaired patch is presented in Figure 2-6 (e) (Maher *et al.* 2001, Prowell and Franklin 1996, Lavorato *et al.* 2013).

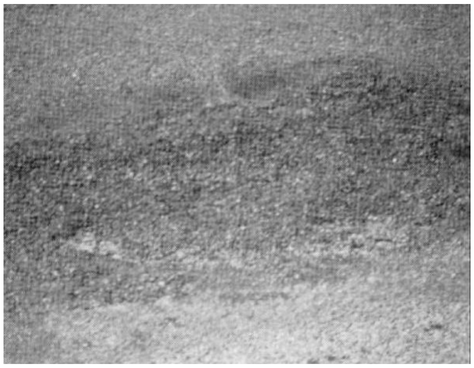
Dishing: Dishing is a bowl-shaped deformation of the repaired patch. It is caused by inadequate compaction during patching, which leads to insufficient stability. When compaction is not done properly during a patching operation, the mixture is subjected to further compaction under traffic loading. The additional compaction creates a bowl-shaped deformation on top of the patch surface (Maher *et al.* 2001, Prowell and Franklin 1996, Lavorato *et al.* 2013).



(a) Cracking (b) Bleeding



(c) Edge disintegration (d) Shoving

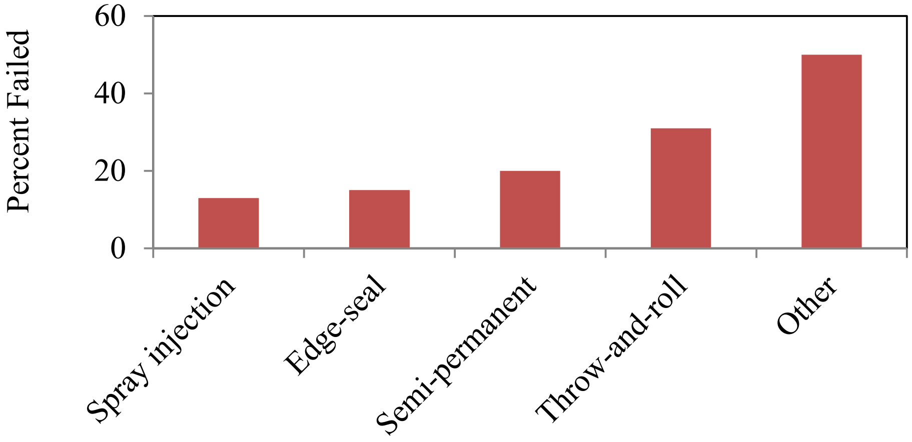


(e) Raveling

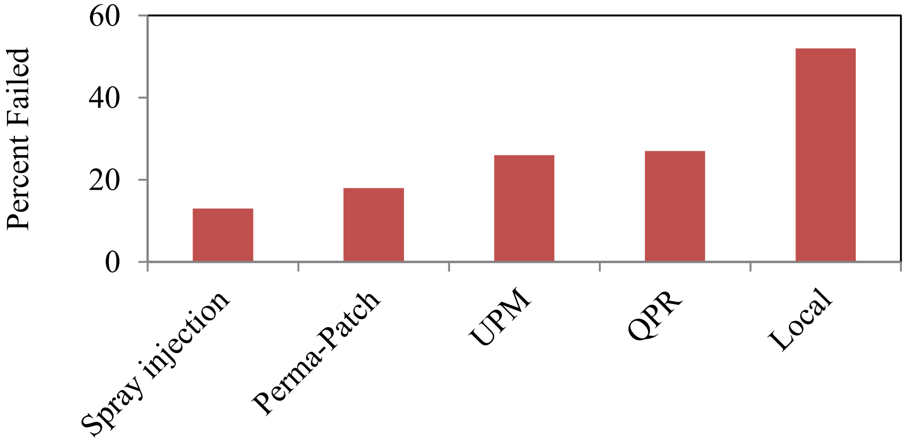
Figure 2-6: Distresses on a repaired patch (Maher et al. 2001)

2.6. Previous studies

A number of field survey and laboratory tests have been conducted to evaluate the performance of different combinations of pothole patching materials and methods. A comprehensive study was conducted by Thomas and Anderson in 1986 to investigate the longevity of pothole repair procedures and their cost-effectiveness based on a two-year field observation in the northern snow-belt states. The results indicated that the rigorous repair procedures, including cutting, cleaning and compacting, are the most cost-effective patching methods. The 'throw-and-go' procedure has been found to be three times more costly than rigorous procedures (Thomas and Anderson 1986). However, the most extensive experiment on pothole patching was conducted from 1991 to 1996 under the SHRP H-106 project. This project included both laboratory tests of patching materials and field evaluations of installed patches across the United States and Canada. To investigate the cost-effective combination of materials and procedure, 1,250 potholes were placed using different installation techniques and patching materials, including proprietary, state-specified and local cold-mix. Survival and distress data were collected following a certain time interval for 18 months. The research has found that durability of patches is higher in the dry-freeze regions than in the wet-freeze regions. 'Throw-and-roll' has been found to be the most cost-effective method. Effectiveness of the 'throw-and-roll' method is similar to that of the semi-permanent method, and productivity is the same as the spray-injection procedure. Among the patching materials, the local materials showed poorer performances. From the distress data, raveling was the most significant post-patching distress. Survival data of repaired patches are presented in Figure 2-7 (Wilson and Romine 1993, 1994, 2001).



(a)



(b)

Figure 2-7: Percentage of repaired patch failed after an observation period of 18 months by (a) patching method and (b) patching materials (Wilson and Romine 1993)

Several laboratory tests were conducted to evaluate the performance of cold mixes. In 1996, 13 proprietary cold-mix patching materials were tested under the Virginia Department of Transportation through a 12-month field survey and laboratory tests that included coating, stripping, draindown, cohesion, asphalt content and gradation, workability and adhesion tests. The test result indicated that dishing, raveling and bleeding are the most common distresses for repaired patch failure. The most important properties of a patching material were identified as stability and survivability (Prowell and Franklin 1996). The New Jersey Department of Transportation performed field surveys as well as laboratory tests to evaluate pothole patching materials and repair procedures. The cold patching materials tested in the laboratory included QPR, IAR, Performix, PermaPatch, Suitkote, UPM, and WesPro. Laboratory tests consisted of Marshall Stability, resilient modulus, blade resistance and rolling sieve test. In the test results, QPR proved to be a more workable and IAR a less stable material among the tested mixtures. Moreover, QPR, Performix and Permapatch displayed excellent results in cohesion and indirect tensile strength according to Table 2-2 (Maher *et al.* 2001).

Table 2-2: Laboratory test results of cold patching materials (Maher et al. 2001)

Material	Marshall Stability (N)	Indirect Tensile Strength (kPa)	Blade Resistance (N)	Rolling Sieve (% retained)
QPR	5472.8	510.6	378.1	93.6
IAR	3220.4	N/A	668.1	N/A
UPM	4952.4	613.4	608.5	21.8
Performix	4938.2	629.8	793.5	98.3
PermaPatch	6528.8	515.2	587.1	91.7
Suitkote	4752.2	418.9	858.5	95.6
WesPro	9937.3	393.0	627.6	7.4

Another laboratory evaluation of cold patching materials was conducted by the Oregon Department of Transportation (ODOT). The evaluation procedure included gradation, workability, cohesion and binder coating test. Workability of different cold patching materials was investigated following the AASHTO TP43-94 standard test method. Test results of some materials are summarized in Table 2-3. All of the four mixes were considered to be suitable workable materials because they had a workability number less than three. However, the workability of Instant Road Repair (IRR) and PermaPatch is higher than the other two. A cohesion test was conducted following the AASHTO TP44-94 standard test procedure, and the FHWA recommended minimum cohesion value was

60% for pothole patching materials. From the test results, cohesion values of the four cold mixes were found satisfactory. A binder coating test was performed following the AASHTO TP40-94 standard test method, and the minimum coating specification is 90% according to the FHWA pothole manual. The test results indicated that all of the materials passed the criteria for coating (Marcus and Elizabeth 2001).

Table 2-3: Workability, cohesion and coating test results of cold patching materials (Marcus and Elizabeth 2001)

Material	Workability (#)	Cohesion (% retain)	Coating (%)
QPR2000	1.0	100	95
UPM	2.0	99.9	99
PermaPatch	0.75	66.6	99
IRR	<=0.5	99.7	99

A laboratory performance evaluation of pavement pothole patching materials was conducted under simulated traffic loading with a ball joint and rubber membrane and environmental temperature effect consisting of freeze and thaw cycles. During this test, the post-patching distresses were monitored by visual observation (El-Korchi 2007). Winter season pothole patching materials were evaluated in Tennessee through a six-month field survey and laboratory tests. Field survey results indicated that edge disintegration and missing patch are the two common distresses for patches repaired using the 'throw-and-roll' method. In addition, three cold mixes and HMA were tested in the laboratory. Freeze-thaw resistance, rutting potential and bonding of patching materials were investigated through adhesiveness, cohesion, moisture susceptibility and loaded wheel test. Adhesion and strength of HMA has been found to be much higher than cold mixes (Dong and Huang 2013, Dong *et al.* 2014a). In another study, long-term cost-effectiveness of 'throw-and-roll' and semi-permanent repair methods was evaluated from a 14-month field survey. It was pointed out that the semi-permanent procedure is more cost-effective in the case of long-term phenomenon (Dong *et al.* 2014b). Influence of different factors on field serviceability of 'throw-and-roll' pothole patches were investigated through a 14-month field survey in Tennessee. The result specified that material type and weather conditions have a significant effect on service life of patches (Dong *et al.* 2015).

A nationwide questionnaire survey and field assessment conducted by the Tennessee Department of Transportation showed that ‘throw-and-roll’ is widely used and cost-effective when applied at spring season due to the higher durability of spring-repaired patches. On the other hand, the semi-permanent patching method is expensive for a one-time repair but cost-effective on a long-term basis (Dong *et al.* 2014c). Another national survey was conducted by the Ohio Department of Transportation to compare the performance of the ‘throw-and-roll’ and spray injection patching method with the infrared asphalt heater/reclaimer patching method. The survey result indicated that the infrared asphalt heater/reclaimer patching method can be cost-effective but has lower productivity (Nazzal *et al.* 2014). In 2011, a questionnaire survey was conducted around Europe in order to study medium- or long-term repair of potholes and provide road agencies an overview of the possibilities for repairing potholes. The survey result indicated that hot- and cold-applied bituminous material, cementitious material and synthetic binder are normally used for pothole patching (Nicholls *et al.* 2014).

Chapter 3. Investigation on Pothole Maintenance in Canada throughout Questionnaire Survey

3.1. Abstract

This paper investigates the severity of the pothole problem in Canada by conducting critical assessments of current maintenance practices and identifying resources available for pothole repair throughout the country. For this purpose, a questionnaire was designed and distributed across the transportation agencies in Canada. The results of the six provincial transportation agencies of Alberta (AB), Manitoba (MB), Ontario (ON), Quebec (QC), Saskatchewan (SK) and New Brunswick (NB) were analyzed and presented in this paper.

According to the survey outcomes, a greater percentage of moderate to high severe potholes was noticed in the study area. Low severe potholes are common in provinces with good road conditions. Freeze-thaw cycle was identified as the most influential factor in pothole formation. A large portion of pothole repair operations are conducted in the summer period due to good weather conditions. The frequently used pothole patching materials were identified as conventional cold mix (CCM), hot mixed asphalt (HMA), quality pavement repair (QPR) and innovative asphalt repair (IAR). The 'throw-and-go' method is commonly used for pothole repair operations in all seasons. Durability of a winter-repaired patch is significantly less than that of a summer-repaired patch. Raveling, edge disintegration and cracking are the most concerning distresses of patch failure, all of which result from inadequate stability, adhesion, cohesion and stripping potential of patching materials.

3.2. Introduction

3.2.1. Background

Flexible pavement structures consist of an asphalt surface course with an underlying base and subbase course on top of a subgrade layer. Surface course contains well compacted, highest quality bitumen mix and contributes to most of the pavement strength. The layer underneath the surface course is base, which contributes to load distribution, drainage and frost resistance. This layer consists of stabilized or unstabilized durable aggregates while the subgrade layer contains well compacted soil (Jassal 1998). However, flexible pavement is subjected to distresses and disintegrations as a result of pavement materials, subgrade soil conditions, traffic loading and environmental factors. A pothole is a common deterioration among flexible pavements that mostly occurs in cold regions where adverse weather conditions accelerate pavement distresses. Multiple cold regions can be found across Canada, and most of the provinces experience low yearly average temperatures. Hence, the pothole problem is very severe and one of the most concerning issues in this area. Potholes can be defined as bowl-shaped depressions of varying sizes that penetrate all the way through the top layer down to the base course, frequently encountered on the surface of flexible pavements. Potholes are classified into different severity categories depending on the depth of the hole. A pothole less than 25 mm deep is in the low severe category. A pothole 25 mm to 50 mm deep is in the moderate severe category. Finally, a pothole more than 50 mm deep is in the high severe category (Miller and Bellinger 2003). In flexible pavement, potholes are created from more severe interconnected fatigue cracks, longitudinal cracks or raveling of pavement surface (Dong *et al.* 2014a, Dore and Zubeck 2009). In cold climatic regions, water penetrating into the top layer of asphalt through the cracks leads to pothole generation, which is then accelerated by freeze-thaw cycles. Late winter and early spring are considered the freezing and thawing periods, respectively (Maher *et al.* 2001). Apart from that, the formation of potholes depends on numerous other factors such as material and thickness of pavement, traffic loading, inappropriate repairs, pavement age, rate of precipitation and winter maintenance. Pavement surfaces may crack due to poor support, unsuitable material, inappropriate thickness of pavement layers, and excess traffic loading. Vehicles passing or water penetrating through the cracks into the base layer may cause rapid development of potholes. Moreover, moisture build up beneath the asphalt layer as a result of poor drainage systems may also create potholes. Bituminous pavement surface will develop cracks over time due to oxidation and drying of binder material. Routine preventative maintenance can be considered as a remedial measure for this issue. Furthermore, high precipitation rate over the year and winter maintenance practice, especially snow removal policy, indirectly affect the process of pothole generation (Paige-Green *et al.* 2010).

Patching of potholes is performed under various weather conditions and temperature cycles. The pothole patching season is usually divided into two periods: winter and summer. In winter, pavement is exposed to low temperatures and freeze occurrence is common. On the other hand, thaw is very frequent in spring. As a result, the winter-laid patch receives immediate stress from freeze and has a shorter survival period than the summer patch. The quality of the pothole patching operation depends on the choice of patching material as well as the repair procedure (Wilson and Romine 2001). Various combinations of patching materials and repair techniques can be used in different seasons. A great variety of patching materials, including HMA and cold mixes, are being used for pothole repair in different places of Canada and the USA. Cold patching materials are produced with emulsified or cutback bitumen to increase workability in cold weather and antistripping agents to reduce moisture susceptibility (Prowell and Franklin 1996). The most widely used patching method is ‘throw-and-go’. This simple and quick procedure consists of placing material into the pothole, compacting it using truck tires, and leaving a 3 to 6 mm crown above the pothole. Most often this method is used for temporary repairs in the winter period, and the semi-permanent repair technique is popular for permanent pothole repairs in the summer season. The repairing procedure in a semi-permanent method includes removing water and debris from the pothole, straightening the edges, placing the mixture, and compacting it with specific devices. Other than these two methods, spray injection and edge-seal patching methods are also used for pothole repair (Wilson and Romine 2001). Pothole repair strategy can be evaluated by determining the durability of the patch and monitoring the post-patching distresses. Commonly noticed patch distresses are alligator cracking, bleeding, edge disintegration, missing patch, shoving, raveling and dishing (Prowell and Franklin 1996). However, it is very important to investigate the severity of the pothole problem around Canada and establish the factors responsible for this issue, the current maintenance practices and their effectiveness.

3.2.2. Previous studies

Several studies have been conducted on pothole maintenance in cold regions. In 1986, Thomas and Anderson performed a two-year field observation in the northern snow-belt states in order to determine the longevity of pothole repair procedures and their cost-effectiveness. The results indicated that the rigorous repair procedures, including cutting, cleaning and compacting, are the most cost-effective patching methods. Compared to this procedure, 'throw-and-go' has been found to be three times more costly (Thomas and Anderson 1986). The Strategic Highway Research Program (SHRP) H-106 project is some of the most extensive work on pothole patching. In this project, performance of different materials, procedures and equipment for pothole repair were evaluated based on cost-effectiveness. As part of this project, field evaluations of installed patches were conducted across the United States and Canada, evaluating materials such as proprietary, state-specified, and local cold-mix patching materials and several different installation techniques. The outcomes of this research showed that 'throw-and-roll' is more economical and as effective as the semi-permanent patching method. On the other hand, it was also found that expertise of the operator is an important factor when measuring the effectiveness of spray-injection patching (Wilson and Romine1993, 1994, 2001). The Oregon Department of Transportation (ODOT) has conducted a survey to investigate pothole patching methods and equipment utilized by local transportation agencies in winter periods. The results indicated that spray patch is the most widely used and efficient method for winter pothole patching (Griffith 1998). In another study, long-term cost-effectiveness of 'throw-and-roll' and semi-permanent repair methods was evaluated from a 14-month field survey. It was pointed out that semi-permanent is a more cost-effective procedure in cases of long-term phenomenon (Dong *et al.* 2014b). The results from a nationwide questionnaire survey conducted by the Tennessee Department of Transportation (TDOT) showed that 'throw-and-roll' is the most widely used method and semi-permanent is the most cost-effective method (Dong *et al.* 2014c). The performances of the 'throw-and-roll' and spray injection patching methods were compared with the infrared asphalt heater/reclaimer patching method based on the output of a national survey conducted by the Ohio Department of Transportation (ODOT). The survey results found the infrared asphalt heater/reclaimer patching method to be cost-effective but less productive (Nazzal *et al.* 2014). In 2011, a questionnaire survey was conducted throughout Europe in order to study medium- or long-term pothole repairs and provide road agencies an overview of the possibilities for the pothole repairs. The survey results indicated that hot and cold applied bituminous material, cementitious material and synthetic binder are normally used for pothole patching (Nicholls *et al.* 2014). Furthermore, a 14-month field investigation found that material type and weather conditions have a significant effect on the service life of 'throw-and-roll' pothole patches (Dong *et al.* 2015).

3.2.3. Objectives and scope

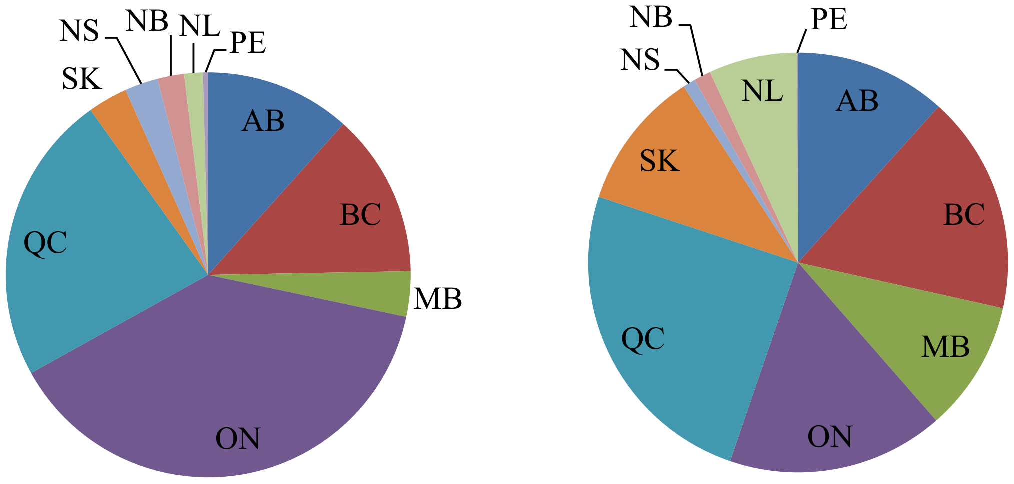
The main objectives of this study are divided into the following sections.

1. Investigating the severity of the pothole problem throughout Canada.
2. Establishing the factors responsible for pothole development.
3. Identifying current practices of pothole patching in different regions in Canada.
4. Studying the performance of patching techniques based on survival period and post-patching distresses.

In order to acquire data to fulfill the above objectives, a questionnaire was developed and distributed to transportation agencies in six provinces of Canada, including Alberta, Manitoba, Ontario, Quebec, Saskatchewan and New Brunswick. The questionnaire gathered information on the characteristics of road networks maintained by the agency; factors responsible for pothole formation; pothole repair strategy combining repair season, patching material and method; efficiency of various repair techniques; pavement repair budget; and suggestions for future developments in pothole repair. In addition, population and weather data for the provinces of Canada were collected. The findings from the questionnaire are analyzed and the results are presented in this paper.

3.3. Population, land area and weather in Canada

This section discusses a general overview of distribution of population and land area in the ten provinces of Canada. Additionally, climate information, including annual average temperature, annual precipitation and yearly snowfall, was also gathered for all the provinces.



(a)

(b)

Figure 3-1: Distribution of (a) population and (b) land area in Canada

The population and land area distribution among Canada's ten provinces are presented in Figure 3-1 (Government of Canada, Statistics Canada 2015). This Figure shows that at approximately 25%, Quebec occupies the largest part of the total land, and its population is almost one fourth of the total population of Canada. Ontario covers 17% of the total land of Canada, yet its population is the largest compared to all other provinces. British Columbia also covers 17% Canada, but its population does not exceed 13%. Alberta, Manitoba and Saskatchewan each occupy 10–12% of the total land area, though the population in Manitoba and Saskatchewan is very low. Newfoundland and Labrador also has a small population compared to the land area, and Nova Scotia, New Brunswick and Prince Edward Island are small provinces.

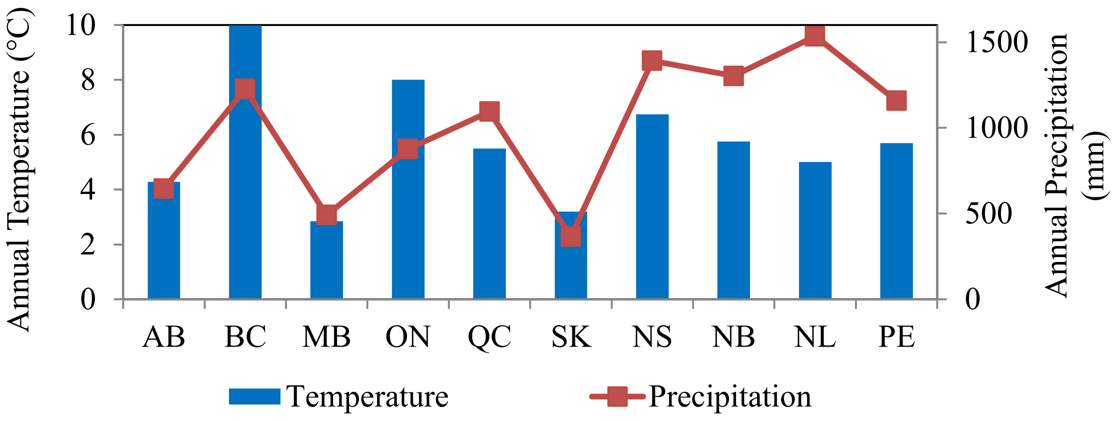


Figure 3-2: Plot of annual temperature and precipitation for provinces in Canada

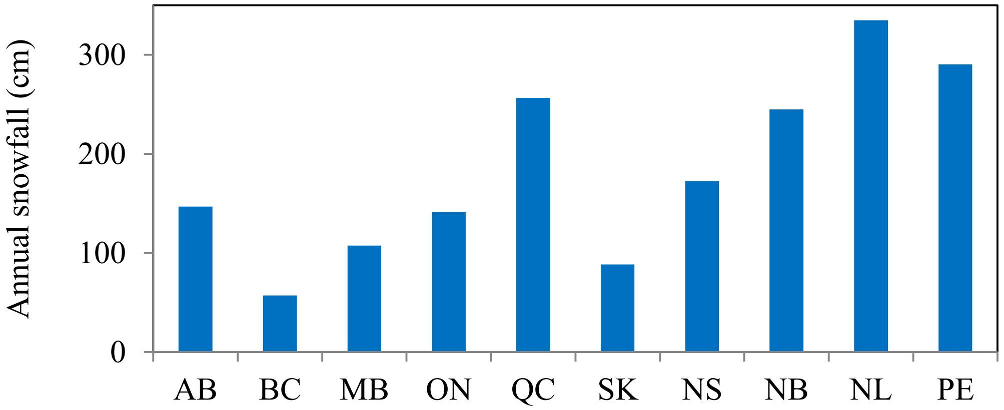


Figure 3-3: Plot of annual snowfall for provinces in Canada

Figure 3-2 and Figure 3-3 present the average annual temperature, precipitation and snowfall of the provinces in Canada. These figures demonstrate that British Columbia is the warmest province with the highest yearly average temperature and the lowest annual snowfall. Ontario is the second warmest province in Canada with moderate snowfalls. Ontario's annual average temperature is almost twice that of Alberta, although they have similar annual snowfall. Alberta, Manitoba and Saskatchewan can be considered the three coldest provinces because of the lower yearly average temperature; however, their annual snowfall is not very high compared to other provinces. The highest yearly snowfall occurs in Newfoundland and Labrador, Prince Edward Island, Quebec and New Brunswick. The annual temperatures of Quebec, Nova Scotia, New Brunswick, Newfoundland and Labrador and Prince Edward Island are in the range of 5°C to 6.8°C, but the yearly precipitation rates of Quebec and Prince Edward Island are lower than others (Government of Canada, Climate 2015).

Canadian provinces are classified into different climatic zones presented in Table 3-1. Alberta, Manitoba and Saskatchewan are in a dry-high-freeze zone with a lower annual precipitation rate and lower yearly average temperature among the provinces. On the other hand, Ontario and Quebec are located in a wet-high-freeze zone with a relatively higher precipitation rate. The rest of the provinces are situated in a wet-low-freeze zone (Tighe 2006).

Table 3-1: Climatic zones for individual provinces in Canada

Climatic zone	Canadian provinces
Dry-high-freeze	AB, MB, SK
Wet-high-freeze	ON, QC
Wet-low-freeze	BC, NS, NB, NL, PE

3.4. Questionnaire survey on pothole maintenance

The survey questionnaire has been categorized into five parts. The first part includes general questions about the road network together with traffic data and presents roadway conditions. This section also contains information about the structure of flexible pavements. The second part consists of the causes and scale of pothole generation. The third part comprises more detailed information on pothole patching materials and repair methods for both summer and winter seasons. Moreover, the survival period and deterioration process of a repaired patch are covered in the third part. The forth part focuses on pavement repair budgets as well as budgets for pothole repair. The fifth section collects information regarding experts' opinions about possible future improvements in pothole repair strategies. Appendix A shows a sample of the survey questionnaire. Canadian provincial and highway agencies have been requested to participate in this survey because of their extensive expertise in pavement maintenance techniques in cold climate regions.

3.4.1. Questionnaire result

3.4.1.1. Network characteristics

This section of the questionnaire responses contains information about the total network size, condition of major arterial roads, percentages of each type of pavement and present conditions of roadways maintained by the agency. Each section is discussed separately below.

a) Network size

From the obtained responses, it is clear that both Alberta Transportation and Quebec Ministry of Transportation maintain two of the largest road networks, though the land and population of Quebec are twice that of Alberta. Manitoba, on the other hand, covers a small network compared to Saskatchewan in spite of both provinces occupying similar sized areas of land. As a small province of only 1.3% of the total land, New Brunswick is maintaining a portion of overall networks that is comparable to that of Ontario. Network sizes maintained by different organizations are presented in Table 3-2.

Table 3-2: Network size maintained by different organizations

Agency/Organization Name	Network size
Alberta Transportation	31,400 Centerline-kilometer
Quebec Ministry of Transportation	30,600 Centerline-kilometer
Saskatchewan Ministry of Highways and Infrastructure	26,162 Centerline-kilometer
Ontario Ministry of Transportation	17,000 Centerline-kilometer 40,000 Lane-kilometer
New Brunswick Department of Transportation and Infrastructure	36,004 Lane-kilometer
Manitoba Infrastructure and Transportation	12,500 Centerline-kilometer 25,000 Lane-kilometer

b) Condition of major arterial roadways

Focusing on the present conditions of major arterial roadways across Canada, this part of the questionnaire gathered information about their total lengths, percentages of truck traffic and the Annual Average Daily Traffic (AADT) presented in Table 3-3. Alberta, Ontario and Quebec have more than 6,000 kilometers of major arterial roads, while other provinces have a much lower number. Major arterial roadways cover a significant portion of the total road network for the listed provinces. The percentage of truck traffic is in the range of 12–20%. However, AADT in major arterial roadways is relatively higher in Alberta compared to other provinces.

Table 3-3: AADT, percentage of truck traffic, kilometer length and percentage of total network of major arterial roadways

Province	AADT	Percentage of truck traffic	Length in kilometers	Percentage of total network
AB	13,200	19	6,150	20
MB	6,500	20	1,600	32
ON	7,000	16	7,500	44
QC	4,000	12	8,600	28
NB	5,000	15	1,786	26

c) Pavement types and conditions

This part of the questionnaire focuses on the present conditions of different roadway classes and pavement types. To investigate the present conditions of roadways, roads are classified into five groups: local, collector, minor arterial, major arterial and freeway. The responses presented in Table 3-4 show that both major arterial and freeway roads are in very good condition. The overall present condition of roads in Alberta and Ontario is good except the local roads, which are in fair condition. Saskatchewan and New Brunswick reported poor local roads. However, collector and minor arterial roads are fairly good, and major arterial roads and freeways are in good to very good condition in these two provinces.

Table 3-4: Present conditions of roadways in different provinces according to PQI (Pavement Quality Index) or PSR (Present Serviceability Rating)

Province	Present condition of pavements for different classes of road					
	Local	Collector	Minor arterial	Major arterial	Freeway	Other
AB	Fair	Good	Good	Good		
ON	Fair	Good	Good	Very Good	Very Good	Good
SK	Poor	Fair	Fair	Good	Good	
NB	Poor	Fair	Fair	Good	Very Good	

Here,

Very good: PQI (≤ 10.0) or PSR (4-5)

Good: PQI (≤ 8.5) or PSR (3-4)

Fair: PQI (≤ 7.0) or PSR (2-3)

Poor: PQI (≤ 5.0) or PSR (1-2)

Very poor: PQI (≤ 3.5) or PSR (0-1)

Table 3-5 presents the percentage of flexible, rigid and other roadways, and it demonstrates that flexible pavement is the prevalent type of pavement in Canada. Manitoba and Saskatchewan have comparatively lower percentages of flexible pavement than the other provinces. Rigid pavements are very rare and only an insignificant percentage is present in Manitoba, Ontario and Quebec. A small portion of other roads is also noticed here. In most cases, they consist of gravel roads. However, across the study area, an average of 76% of roads is flexible pavement.

Table 3-5: Pavement types in different provinces by percent

Province	Pavement types (%)		
	Flexible	Rigid	Other
AB	89.3	0.2	10.5
MB	59	3	38

ON	79	1	20
QC	88	3	9
SK	57	0	43
NB	84.2	0.06	15.74

3.4.1.2. Properties of flexible pavement

Information about the properties of flexible pavement, including the typical thickness of asphalt layer and type of base layer, were collected from the survey. Table 3-6 represents the commonly used asphalt thicknesses for six Canadian provinces. Asphalt thickness is almost the same for all road types in Saskatchewan and New Brunswick. In most provinces, local pavement is constructed with asphalt thickness of 50 to 80 mm. For local roads in Quebec, the thickness of asphalt layer is selected based on AADT. A local road having AADT greater than 2,000 requires an asphalt thickness of 115 mm. In Manitoba and Quebec, the variation of asphalt thickness is lower for all classes of roads.

Table 3-6: Thickness of asphalt layer for different classes of roadway

Province	Asphalt thickness (mm)				
	Local	Collector	Minor Arterial	Major arterial	Freeway
AB	140	200	240	270	
MB		85-100	100	150	≥150
ON	50	80	50	100	200
QC	75-115	100-155	< 130	155	>150
SK	80	80	80	80	120
NB	140	140	140	140	140

Granular material is very popular and thus widely used as a base layer for all classes of roadways in most of the provinces. The exception is Ontario, where stabilized base is commonly used for local and collector roads and bituminous base is used for arterials and freeways.

3.4.1.3. Causes of pothole development

This part of the questionnaire includes a number of probable factors based on previous studies that cause or accelerate the development of potholes in cold climates. The rating of different factors for pothole generation is presented in Table 3-7.

Table 3-7: Rating of probable causes of pothole development in different provinces (Scale: 1 to 5, where 5 is most important cause)

Causes	AB	MB	ON	QC	SK	NB
Freeze-thaw cycles	5	5	4	3	5	5
Traffic load	4	4	4	3	5	4
Poor subgrade soil	3	2	3	5	3	3
Poor asphalt mixture	1	2	5	2	3	2
Poor drainage	3	3	4	5	4	4
Pavement age	2	4	4	4	4	5
High ground water table	3	2	3	5	3	2
High precipitation over the year	1	4	2	4	3	3
Inappropriate repair of pothole	1	1	4	4	2	3
Late rehabilitation of other distresses	1	3	3	3	3	5
Winter maintenance practice	1	1	5	4	2	2
Other			4	2		

Literature confirms that the freeze-thaw cycle is the most probable and thus the most investigated cause of pothole development. Two thirds of the total responses also state that the freeze-thaw cycle is the most probable reason for pothole formation. Traffic load and pavement age are considered to be the second largest cause of pothole formation, which is also confirmed by two thirds of the total responses. Apart from that, 50% of the responses mention poor drainage as the second leading cause of pothole development. Another third of the responses identified these two issues as less important. Poor subgrade soil, high ground water table and late rehabilitation of other distresses are rated as the third leading cause of pothole development on a scale of 1 to 5 (5 being the most important cause) by more than 50% of the responses. Winter maintenance policy is seen as a less crucial issue by two thirds of the participants with the exception being Ontario, who identifies it as one of the most serious causes. Poor asphalt mixture, high precipitation rate over the year and inappropriate repair of potholes all provoked a variety of answers. A portion of the responses rated these three issues from medium to less important, and another portion identified them as being more serious causes for pothole development. Ontario listed thin depth of repaired potholes as one of the critical factors. Figure 3-4 shows the average rating of factors responsible for pothole formation. The most concerning factors are freeze-thaw cycles, traffic load, poor drainage and pavement age.

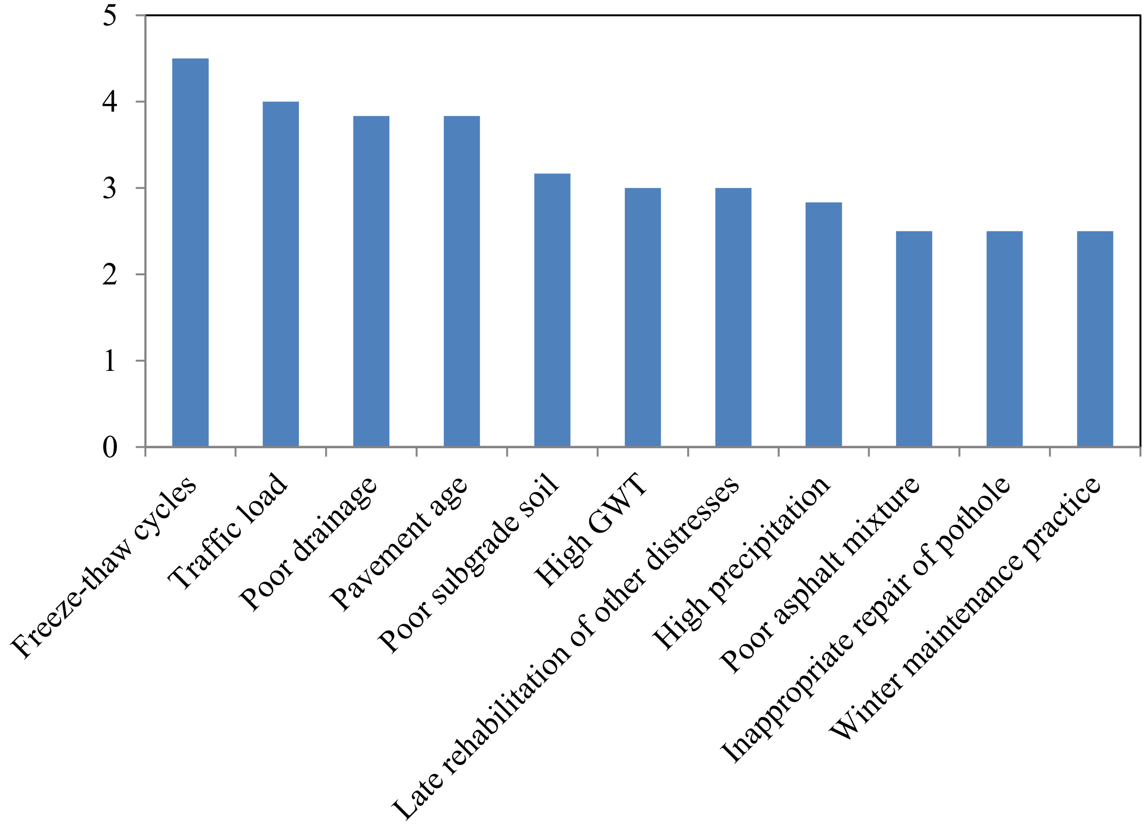


Figure 3-4: Average rating of probable causes of pothole development in different provinces (Scale: 1 to 5, where 5 is most important cause)

3.4.1.4. Severity of the pothole issue in Canada

To investigate the severity of the pothole problem in Canada, data on the distribution of distress severity of repaired potholes were collected and presented in Table 3-8. Potholes are classified into three categories depending on their depth. Manitoba, Quebec and New Brunswick contain a greater percentage of high severity potholes. Most of the developed potholes are of low severity in Ontario and moderate severity in Alberta and Saskatchewan.

Table 3-8: Percentage of potholes in three categories of severity

Province	Distribution of distress severity of repaired pothole (%)		
	Low	Moderate	High
AB	40	58	2
MB	10	30	60
ON	80	15	5
QC			100
SK	-	70	-
NB	20	40	40
Average	26	38	36

3.4.1.5. Pothole repair

The pothole repair operation is divided into three separate sections: repair period, repair material and repair method. Their combination is crucial when considering the survival period and deterioration of a repaired patch. The main goal of this questionnaire section was to identify the current practices of pothole repair operations in Canada and investigate their effectiveness. Each section of pothole repair strategy is discussed below.

a) Repair period

In general, pothole repair operations, also referred to as pothole patching, are performed in the winter and summer periods. Because of the adverse weather conditions in winter, pothole patching is only performed as an emergency repair. On the other hand, due to mild favourable weather in summer, potholes can be repaired as part of a routine maintenance schedule (Wilson and Romine 2001). This section of the paper focuses on pothole repair strategies as well as repair periods in different parts of Canada.

The information gathered from the transportation agencies suggests that pothole repair operations are mostly done in the summer; only a small number of potholes are repaired during winter. In Ontario and Quebec, approximately 40% of pothole repair operations are performed in winter. Table 3-9 represents the percentage of pothole repair operations in summer and winter for different provinces.

Table 3-9: Periods of pothole repairs

Province	Winter Repairs (%)	Summer Repairs (%)
AB	10	90
MB	10	90
ON	40	60
QC	43	57
SK	10	90
NB	10	90

b) Repair material

An extensive literature review was conducted to gather information on the pothole repair materials used for patching in cold climates. Table 3-10 represents the percentages of four types of pothole repair materials used for both winter and summer repairs in six provinces across Canada. The responses identify four types of widely used mixes. Almost all of the provinces are using similar materials for summer and winter repairs. Quality pavement repair (QPR), a proprietary cold mix, is used for patching in Alberta, Manitoba and Saskatchewan in winter and summer and in New Brunswick in winter; however, New Brunswick only uses HMA for summer patching. Conventional cold mix (CCM) is another widely used material, especially in Ontario and Quebec. A small portion of potholes are repaired with HMA in Ontario, Quebec and Saskatchewan. Innovative asphalt repair (IAR) is a high quality permanent repair patching material that consists of proprietary bituminous liquid blend and aggregate (Maher *et al.* 2001). It is used for 50% of the total patching operations in Manitoba. Spray injection material is used for a small portion of summer pothole repairs in Quebec.

Table 3-10: Pothole repair materials used in summer and winter in six provinces in Canada

Province	Winter repair material (%)				Summer repair material
	CCM	HMA	QPR	IAR	
AB	15	0	85	0	Same as winter
MB	0	0	50	50	Same as winter
ON	60	40	0	0	Same as winter
QC	75	25	0	0	Same + 5% spray injection
SK	20	20	60	0	Same as winter
NB	0	5	95	0	HMA

c) Repair methods

Pothole patching includes four different methods: (a) throw-and-go, (b) semi-permanent, (c) edge seal, and (d) spray injection. The 'throw-and-go' method is known in the literature as the most common and widely used technique of pothole patching, a claim that is also confirmed by the survey responses. The survey responses also indicated that this method is commonly used for winter pothole repair. Table 3-11 represents a summary of pothole patching methods used in different provinces in winter. The semi-permanent method is considered to be one of the best methods of patching for producing a permanent patch despite being costly, time consuming and requiring more workers and equipment. This repairing technique is also used in some parts of Canada, particularly in Ontario and Saskatchewan. Most provinces use similar techniques for summer and winter repairs. The spray patch method is commonly used for summer patching in Alberta. It is a quick repair method but it requires specialized equipment with a truck and trailer or a self-contained unit. Asphalt pavers are used for summer pothole repair in Quebec. In New Brunswick, the semi-permanent method and clean, patch, compact procedures are common for summer repairs.

Table 3-11: Pothole patching methods for winter repair

Province	Throw-and-go (%)	Semi-permanent (%)

AB	100	0
MB	100	0
ON	60	40
QC	80	20
SK	70	30
NB	95	5
Average	84	16

3.4.1.6. Performance of different repair techniques

To investigate the performances of different combinations of patching materials and methods, the survival periods of repaired patches for both summer and winter periods were collected from the provinces of Canada. Also included was information about the major distresses that cause failure of the repaired pothole.

a) Survival period of repaired patch

The responses indicate that a pothole repaired in summer lasts longer than that repaired in winter. In Alberta and New Brunswick, survival periods of winter-repaired potholes are hardly three months, whereas they last three to six months in Ontario and Saskatchewan and six to nine months in Quebec. The highest survival period of winter-repaired patches is observed in Manitoba, where they range from nine months to one year. On the other hand, the minimum survival period of repaired potholes in summer is one to one and a half years in Ontario and Quebec. This time period is one and a half to two years in Saskatchewan, and more than two years in Alberta, Manitoba and New Brunswick. A summary of survival periods of repaired patches for different provinces is gathered in Table 3-12.

Table 3-12: Survival periods of repaired patches for provinces in Canada

Repair period	Provinces	Survival Period						
		< 3 months	3-6 months	6-9 months	9 months – 1	1-1.5 years	1.5-2 years	> 2 years

					year			
Winter	AB	✓						
	MB				✓			
	ON		✓					
	QC			✓				
	SK		✓					
	NB	✓						
Summer	AB							✓
	MB							✓
	ON					✓		
	QC					✓		
	SK						✓	
	NB							✓

b) Causes of repaired pothole failure

A number of causes for patch failure were listed in the survey, including cracking, bleeding, edge disintegration, missing patch, shoving, raveling and dishing. The respondents were asked to rate the listed causes on a scale of 1 to 5 with 5 being the most common cause of patch failure. The rating of the probable causes of patch failure is presented in Table 3-13.

Table 3-13: Rating of probable causes of repaired pothole failure (Scale: 1 to 5, where 5 is most important cause)

Causes	AB	MB	ON	QC	SK	NB
Cracking	5	3	4		4	2
Bleeding	1	1	1		1	2
Edge disintegration	1	4	3	5	3	5
Missing patch	1		3		5	2
Shoving	1	1	5		2	
Raveling	3	3	4	5	1	5

Dishing	1	1	2			
Other			4			

Raveling, edge disintegration and cracking were identified by 50% of responders as major causes of patch failure and rated as 4 to 5. One third of responses rated them as 3. Poor cohesion of the patching mixture and improper compaction during patching operation results in raveling distress. As well, inadequate adhesion of the patching material causes cracking and edge disintegration of the repaired patch. Missing patch and shoving were identified as the most important problems for pothole development by Saskatchewan and Ontario, respectively, whereas all other responders reported them as minor issues. Patching material loss occurs due to a lack of adhesion and cohesion of the patching material. Material with poor stability causes vertical or horizontal movement of a patch, which is normally known as shoving. Insufficient compaction during pothole patching can create both shoving and missing patch distresses. Among all of the post-patching distresses, bleeding and dishing were rare occurrences. Inadequate voids and excessive binder in the mixture, as well as traffic loading, cause bleeding on the repaired patch. Dishing is normally a result of inadequate compaction during patching, which leads to insufficient stability. However, the size of the repaired pothole is rated as 4 in a response from Ontario. Repaired patches in Quebec fail for three main reasons, including edge disintegration, raveling and inadequate compaction. Figure 3-5 represents the average rating of post-patching distresses.

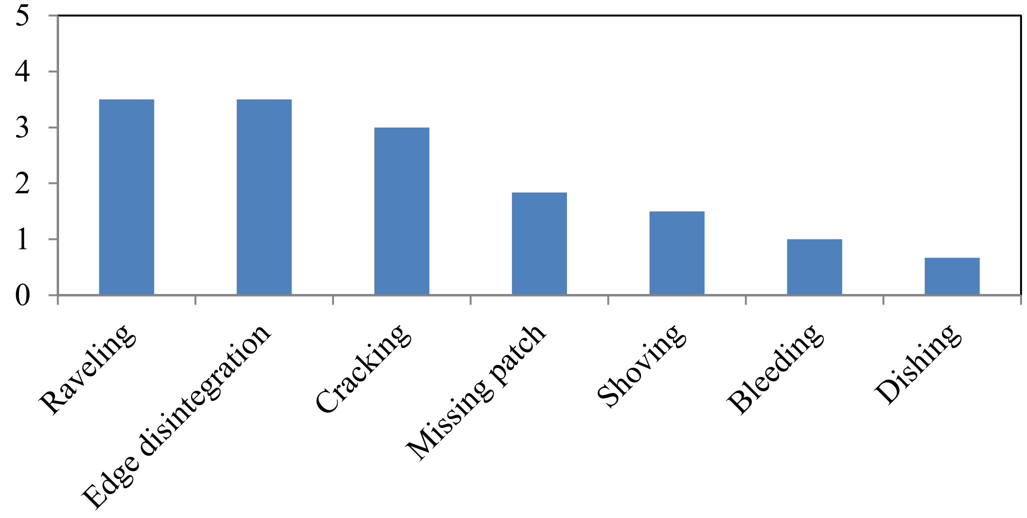


Figure 3-5: Average rating of probable causes of repaired pothole failure (Scale: 1 to 5, where 5 is most important cause)

3.5. Discussion

This paper presented the results of the questionnaire survey on pavement maintenance for potholes with responses received from six cold climate provinces in Canada. The questionnaire results showed that most of the repaired potholes in Alberta and Ontario are of low to moderate severity. The present conditions of roadways have been identified as good to fair for these two provinces. The distress severity categories of repaired potholes are of moderate to high severity for Manitoba, Saskatchewan and New Brunswick. Fairly good pavement conditions with poor local roads are noticed in Saskatchewan and New Brunswick. However, high severity potholes are observed in Quebec.

To investigate the probable causes of pothole development in Canada, some factors were selected and listed with the questionnaire for ranking. Among the causes of pothole development, the freeze-thaw cycle is regarded as the major factor with an average rating of 4.5. All provinces except New Brunswick are situated in a high-freeze zone with a lower average annual temperature. Thus, freeze-thaw occurrence is very common for the study area. Traffic load is viewed as the second largest factor for pothole development. It is also confirmed in literature as one of the vital reasons for pothole formation. The next most significant causes are poor drainage and pavement age. Apart from that, Quebec mentions subgrade soil condition, ground water table and high precipitation as important causes. It has been found that, Ontario, Quebec and New Brunswick are situated in a wet-freeze zone where the precipitation rate in a year is about 900 to 1,300 mm. At the same time, Manitoba also rated high precipitation as the fourth most important cause, possibly because of having the lowest temperature among the six provinces; however, Manitoba has a comparatively lower yearly precipitation rate. New Brunswick named late rehabilitation of other distresses as one of the main causes. Ontario also identified poor asphalt mixture as an important cause, although stabilized base is used for pavement construction in this province. Moreover, Ontario identified inappropriate repair of potholes and winter maintenance practice as critical factors in pothole development.

As evident by the survey responses, CCM and QPR have been named popular materials for pothole repairs, especially in winter. A small percentage of HMA is also used in some provinces. Alberta and New Brunswick display similar habits in their usage of winter patching materials, repairing methods and survival periods. Particularly, winter patching materials include a greater percentage of QPR with a small amount of CCM or HMA. The ‘throw-and-go’ method is the most commonly used patching technique. In this situation, durability of the patch is no more than three months. Thus, the above technique-material combination for winter repairs is not durable or long lasting, but the durability of the summer repaired patch is more than two years for these provinces. Alberta uses similar repair techniques for summer and winter, whereas HMA with the semi-permanent method is used in New Brunswick. Similar responses regarding patching practices were also collected from Ontario and Quebec. In both provinces, CCM is used for winter pothole repairs along with a combination of the ‘throw-and-go’ and semi-permanent methods. Survival periods of repaired patches are relatively higher in winter but lower in summer compared to that of Alberta and New Brunswick. QPR and IAR are used in the same proportion in Manitoba, where winter durability is the highest among all six provinces. In Saskatchewan, a combination of QPR, HMA and CCM is used for pothole repair operations in winter. Patch durability does not exceed more than six months in winter and two years in summer.

The performance of repair materials and methods can be measured from the durability of the repaired patch and post-patching distresses. In general, the maximum durability of a winter-repaired patch is less than one year, while a summer patch survival period is one to two years or more. Comparing the durability data of repaired patches shows that the best winter repair practice is HMA with the semi-permanent method and CCM with the 'throw-and-go' method. The main causes of patch failure have been noted as raveling, edge disintegration and cracking. Raveling is the most common distress mode of patch failure when a greater percentage of CCM is used as patching material. This distress is caused by stripping, lack of cohesion and presence of excessive fines in the patching mixture. Thus, the stripping potential of CCM can be considered high with lower cohesion. However, cracking and edge disintegration is also noticed in this case. Cracking, caused by inadequate stability, is the most severe patch failure mechanism when QPR and IAR are used as patching materials. Moreover, these materials also have insufficient adhesion and cohesion that cause raveling and edge disintegration.

3.6. Conclusion

The study on pavement maintenance for potholes in cold climate regions depending on questionnaire responses from six provinces in Canada is presented in this paper. Followings are the conclusions based on the questionnaire output.

1 The severity of the pothole problem was investigated throughout the questionnaire results. About three fourths of total developed potholes are of moderate to high severity in this area. Moderate to high severe potholes are noticed in provinces with poor road conditions.

2 The contributions of different factors of pothole development are ranked in this survey, and the most important issues related to pothole formation are identified accordingly. The most influential factor in pothole formation has been identified as the freeze-thaw cycle; traffic load, poor drainage and pavement age have also been named as important issues.

3 According to the responses, about 80% of total pothole patching operations are done in the summer period. CCM, HMA and two proprietary cold mixes (QPR and IAR) are used for winter as well as summer repairs. The ‘throw-and-go’ method is frequently used in Canada for pothole repair operations in all seasons and it covers about 84% of the total patching operation.

4 The overall information regarding the durability of different patching strategies established that the maximum winter patch survival period is one year, while a summer patch can survive from one to more than two years. Although QPR is widely used, the survival period of the repaired patch is low for provinces using a high percentage of this material for winter patching.

5 The most concerning distresses of patch failures are recorded as raveling, edge disintegration and cracking that result from inadequate stability, adhesion, cohesion and higher stripping potential in patching materials. From the performance analysis of pothole repair strategy, QPR and IAR were identified as less stable materials with inadequate adhesion and cohesion, while CCM has been found as a patching material with higher stripping potential and poor cohesion.

Chapter 4. A Study on Pothole Repair in Canada through Questionnaire Survey and Laboratory Evaluation of Patching Materials

4.1. Abstract

Pothole repair in asphalt concrete pavements is one of the most common maintenance operations especially in cold regions. To investigate the severity of pothole problem in Canada, conducting critical assessment of current maintenance practices and identifying resources available for pothole repair throughout Canada, a questionnaire was prepared and distributed to Canadian transportation agencies. According to the survey outcomes from six provinces (Alberta, Manitoba, Ontario, Quebec, Saskatchewan and New Brunswick), a large portion of pothole repairs was typically performed in summer period. Conventional Cold Mix (CCM), Hot Mixed Asphalt (HMA), Quality Pavement Repair (QPR) and Innovative Asphalt Repair (IAR) were identified as most commonly used patching materials in these provinces. Moreover, 'throw-and-go' method was noted as the most commonly used patching procedure during the winter time. Survival period of repaired patches in winter time was significantly less than that of summer time.

To evaluate the performance of patching material, a laboratory testing program was conducted on cold mixes that were identified as the mostly used by the survey. Marshall Stability, Indirect Tensile Strength (ITS) and Tensile Strength Ratio (TSR), adhesiveness and cohesion of the mixtures were evaluated. The laboratory results showed that curing time and temperature had a significant effect on strength gain for all cold mixes. Between three tested cold mixes, CCM showed higher Marshall Stability and cohesion properties, while QPR showed a better moisture resistance and adhesion properties. However, it was noted that all the cold mixes were sensitive to freeze-thaw damage.

4.2. Introduction

4.2.1. Background

Potholes are the most common asphalt pavement deterioration issue occurring mainly in cold regions, where adverse weather conditions accelerate pavement distress. Potholes can be defined as bowl-shaped depressions of varying sizes that penetrate all the way through the surface layer down to the base course, frequently encountered on the surface of flexible pavements (Miller and Bellinger 2003). In flexible pavements, pothole formation begins in a weakened area of the pavement. Usually, a more severe interconnected alligator crack in pavement surface creates a pothole when it breaks down and is affected by the heavy loads of traveling vehicles (Dong *et al.* 2014a). Besides the fatigue cracks, potholes generate from high severe longitudinal cracks or raveling of pavement surface (Dore and Zubeck 2009). Potholes are also generated due to water penetrating the top layer of asphalt through cracks. This process is accelerated by freeze-thaw cycles. Freezing and expanding of water inside the pavement produces additional stresses that result in the breakdown of pavement surface. Moreover, daily freeze-thaw cycles develop voids underneath the pavement, which form potholes after the passing of vehicles across this section (Maher *et al.* 2001). Normally, late winter and early spring is considered to be the freezing and thawing period.

Pothole repair is one of the important flexible pavement maintenance operations. Pothole patching season can be divided into two periods: winter patching and summer patching. Winter patches usually have a shorter survival period as they receive immediate stress from freeze-thaw cycles. The two main components of pothole patching operations are patching materials and different maintenance procedures (Wilson and Romine 2001). Hot mix asphalt (HMA) and cold mixes are normally used as pothole patching materials. Cold mixes are very popular and widely used in cold regions, particularly in winter months. They are produced with emulsified or cutback bitumen to increase workability in cold weather and antistripping agents to reduce moisture susceptibility (Prowell and Franklin 1996).

The ‘throw-and-go’ is the most widely used patching method. This simple and quick procedure consists of placing material into the pothole, compacting using truck tires and leaving a 3 to 6 mm crown above the pothole. Most often this method is used for temporary repair in winter and the semi-permanent repair technique is popular for permanent pothole repair in summer. The semi-permanent repairing procedure includes removing water and debris from the pothole, straightening edges, placing mixture and compacting it with specific devices. Spray injection is another efficient method that consists of cleaning the pothole, spraying tack coat on the sides and bottom of the pothole, blowing mixture and covering the patch area with a layer of aggregate. Edge seal is also known as a patching method that is similar to the ‘throw-and-go’ method. However, this method includes a final step of placing a layer of bituminous tack coat and a layer of sand to prevent vehicle tires tracking over the crown of compacted patch (Wilson and Romine 2001).

4.2.2. Previous studies

A number of field surveys and laboratory tests have been conducted to evaluate the performance of different combinations of pothole patching materials and methods. A comprehensive study was conducted by Thomas and Anderson in 1986 to investigate the durability of pothole repair procedures and their cost-effectiveness based on a two-year field observation in the northern snow-belt of the United States. The results indicated that the rigorous repair procedure that included cutting, cleaning the pothole and compacting the new patching mixture into the pothole was the most cost-effective patching method. The ‘throw-and-go’ method has been identified as three times more expensive (Thomas and Anderson 1986). The most extensive experiment on pothole patching was conducted from 1991 to 1996 under the Strategic Highway Research Program (SHRP) H-106 project. This project included laboratory tests of patching materials and field evaluations of installed patches across the United States and Canada, and it found that the ‘throw-and go’ method was as effective as the semi-permanent method and more cost-effective than the patching method (Wilson and Romine 1993, 1994, 2001). In addition, the Oregon Department of Transportation also conducted a survey to figure out the most common method for winter patching. The survey result identified that the spray patching method was the most widely used and efficient method for winter pothole patching (Griffith 1998).

Several laboratory tests were conducted to evaluate the performance of cold mixes. In 1996, thirteen proprietary cold-mix patching materials were tested under the Virginia Department of Transportation during a 12-month field survey. Laboratory tests included coating, stripping, drain down, cohesion, asphalt content calculation and gradation, workability and adhesion testing (Prowell and Franklin 1996). In 2001, the New Jersey Department of Transportation performed field surveys as well as laboratory tests to evaluate pothole patching materials and repair procedures. The cold patching materials tested in the laboratory included QPR 2000 (Quality Pavement Repair), IAR (Innovative Asphalt Repair), Performix, PermaPatch, Suitkote, UPM (Unique Paving Material) and WesPro. Laboratory tests included Marshall stability, resilient modulus, blade resistance and rolling sieve tests. As demonstrated, QPR was revealed to be a more workable material and IAR a less stable material among the tested mixtures (Maher *et al.* 2001). Winter season pavement patching materials were evaluated in Tennessee under a six-month field survey and various laboratory tests. In this study, three cold mixes and HMA underwent extensive laboratory testing. Freeze-thaw resistance, rutting potential and bonding of patching materials were investigated through adhesiveness, cohesion, moisture susceptibility and loaded wheel tests, and these experiments indicated that the adhesion and strength of HMA are much higher than those of cold mixes (Dong *et al.* 2014a, Dong and Huang 2013). In another study, long term cost-effectiveness of the ‘throw-and-go’ and semi-permanent repair methods was evaluated in a 14-month field survey, eventually confirming that the semi-permanent procedure is more cost-effective as it tends to last longer (Dong *et al.* 2014b). A nationwide questionnaire survey conducted by the Tennessee Department of Transportation characterized the ‘throw-and-go’ method as a widely used one and the semi-permanent method as a cost-effective one (Dong *et al.* 2014c). Another national survey was conducted by the Ohio Department of Transportation to compare the performance of the ‘throw-and-go’ method and the spray injection patching method with the infrared asphalt heater/reclaimer patching method. The survey result indicated that the infrared asphalt heater/reclaimer patching method can be cost-effective, but it has lower productivity (Nazzal *et al.* 2014). Influences of different factors on field serviceability of the ‘throw-and-go’ pothole patches were investigated through a 14-month field survey in Tennessee, and material type and weather conditions were identified as the major factors (Dong *et al.* 2015).

4.2.3. Objectives and scope

The main objectives of this study are divided into three sections:

1. Investigating current practices of pothole maintenance throughout Canada;
2. Determining the performance of different combinations of the patching materials and procedures used through the survival period of repaired patches for both winter and summer seasons;
3. Laboratory performance of the patching materials used according to survey results.

To fulfill the first goal, a questionnaire was developed to gather information about common practices of pothole repair in cold climates from transportation agencies across Canada. According to the survey results from six provinces in Canada (Alberta, Manitoba, Ontario, Quebec, Saskatchewan and New Brunswick), the patching materials used were prepared and tested in the laboratory to evaluate performance.

4.3. Questionnaire survey results

The survey questionnaire included general information about road networks, such as traffic data and present roadway conditions, typical pavement structure, causes and scale of pothole generation, pavement repair budget, as well as pothole repair and experts' opinions about possible future improvements in pothole maintenance. The main focus of this paper falls on analyzing the detailed information of pothole patching materials and methods for both summer and winter seasons considering the survival period of repaired patches obtained through the questionnaire.

4.3.1. Pothole repair

Pothole repair operation has been analyzed according to three separate categories: repair period, patching material and patching method. All the mentioned categories are significant when considering the survival period and deterioration of a repaired patch. One of the most important parts of the questionnaire was to identify the current practices of pothole repair in Canada and evaluate their effectiveness. Each category of a pothole repair operation is discussed below.

(a) Repair period

Because of adverse weather conditions, pothole patching is only done as an emergency repair operation in winter when favourable summer weather allows for the repair in a routine maintenance schedule (Wilson and Romine 2001). The information gathered from the transportation agencies confirms that pothole repair is mostly done in summer, and only a small number of potholes are repaired in winter months. However, about two fifths of total pothole repair operations are performed in the winter season in Ontario and Quebec due to relatively milder winters. Numbers of pothole repair operations in summer and winter seasons for different provinces are presented in Table 4-1.

(b) Patching material

Currently, a great variety of cold patching materials are used for pothole repair in the USA and Canada. Among them, conventional cold mix (CCM) is a common pavement repair material. This mixture consists of dense graded aggregates and is normally used for temporarily fixing potholes (Lavorato *et al.* 2013). Other than that, high performance cold patching materials (QPR, UPM, IAR, Performix, SuitKote, Permapatch and WesPro) are used for winter patching. Spray injection materials consist of crushed aggregates and emulsified asphalt. Apart from cold patching materials, hot mix asphalt (HMA) is also used for pothole repair in summer.

Table 4-1 shows types and amounts of used materials for pothole maintenance in winter in different provinces. The questionnaire responses identify four types of mixes that are widely used for winter patching in Canada. Almost all provinces use similar materials for winter and summer repair. The exception is New Brunswick, where only HMA is used for summer patching. A small percentage of spray injection patching materials are used for summer repair in Quebec. QPR, a proprietary cold mix, is used for winter patching in four provinces of Canada. In Alberta and New Brunswick, most winter repairs are performed using QPR. CCM is widely used in Ontario and Quebec, and a small amount of potholes are repaired with HMA in winter. IAR and QPR are used for patching in Manitoba.

(c) Patching methods

There are four different methods used for pothole patching:

(i) 'throw-and-go';

(ii) semi-permanent;

(iii) edge seal;

(iv) spray injection.

The 'throw-and-go' method is well established in the literature as the most commonly and widely used method of pothole patching. A summary of pothole patching methods used in different provinces in winter is represented in Table 4-1. It can be seen that most provinces use similar techniques for summer and winter repair. The survey responses confirm the 'throw-and-go' method as the most commonly used in pothole repair all over Canada and mainly in the winter season. The semi-permanent method is considered as one of the best methods of patching for producing a permanent patch; even though it is expensive, time consuming and requires more workers and equipment, it is used in Ontario and Saskatchewan. Spray patch is a common repair method mostly used for summer patching in Alberta. It is a quick repairing method, but it requires specialized equipment with a truck and a trailer unit or self-contained unit. In New Brunswick, the semi-permanent method and clean, patch, compact procedures are more common for summer repairs.

Table 4-1: Pothole repair periods, materials and methods in six provinces of Canada

Province	Repair period (%)		Winter patching material (%)				Winter patching method (%)	
	Winter	Summer	CCM	HMA	QPR	IAR	Throw-and-go	Semi-permanent
AB	10	90	15	-	85	-	100	---
MB	10	90	-	-	50	50	100	---
ON	40	60	60	40	-	-	60	40
QC	43	57	75	25	-	-	80	20

SK	10	90	20	20	60	-	70	30
NB	10	90	-	5	95	-	95	5

4.3.2. Performance of different repair techniques

To investigate the performance of different combinations of patching materials and methods, the survival period of repaired patches for both summer and winter periods were collected from the provincial agencies of Canada. It is obvious from the responses that a pothole repaired in summer lasts longer than one repaired in winter. The survival period of winter-repaired potholes is hardly three months in Alberta and New Brunswick, whereas it is more durable in Ontario, Saskatchewan and Quebec. However, the highest survival period of winter-repaired patches is observed in Manitoba. On the other hand, the minimum durability of summer-repaired potholes is noticed in Ontario and Quebec. A comparatively higher survival period is observed in Saskatchewan. Potholes repaired in summer last more than two years in Alberta, Manitoba and New Brunswick. A summary of survival periods of repaired patches for different provinces is gathered in the following Table.

Table 4-2: Survival period of repaired patch for provinces in Canada

Repair period	Provinces	Survival Period						
		< 3 months	3-6 months	6-9 months	9 months – 1year	1-1.5 year	1.5-2 year	> 2 years
Winter	AB	✓						
	MB				✓			
	ON		✓					
	QC			✓				
	SK		✓					
	NB	✓						
Summer	AB							✓
	MB							✓

	ON					✓		
	QC					✓		
	SK						✓	
	NB							✓

4.4. Laboratory tests

The quality of patching materials has a significant effect on durability of the patched pothole. To investigate the quality of used patching materials indicated in the survey, several laboratory tests were conducted. The Marshall stability test was set to evaluate the strength of patching materials, and Indirect Tensile Strength (ITS) testing was performed to determine moisture susceptibility of cold mixes subjected to freeze-thaw cycles. Adhesiveness of the patching materials had been measured to determine the bonding strength of mixtures with pothole edges. At the same time, inner bonding of patching material was investigated in a cohesion test. Material properties, laboratory testing procedures and test results are discussed below.

4.4.1. Material properties

As indicated by the survey results, three cold mix materials were named as commonly used patching materials in six Canadian provinces. The mixes were tested in the laboratory and the obtained results were then compared with those of the HMA.

(a) CCM

For this study, a conventional cold mix was provided by the City of Edmonton. The mixture was composed of granular aggregate, filler and emulsified asphalt. Laboratory sieve analysis of aggregates, as shown in Table 4-3, indicates that the percentage of material retained on the 5-mm sieve was approximately 70%. The plasticity index of the material passing the 0.08-mm sieve was zero. The moisture content of aggregates was not more than 0.5% before mixing with binder. The mixture contained 7.5% emulsified asphalt by weight of dry aggregates and 3% to 5% air void.

(b) QPR

QPR consists of 100% crushed granular aggregates with an open gradation as shown in Table 4-3 and modified bituminous liquid blend. Specific gravity of the aggregates is measured as 2.55% to 2.75%. The mixture contains 4.0% to 6.0% bitumen by weight of mixed material. Aggregate coating with bitumen is 95% and this material remains cohesive up to -26°C (QPR Material Specification).

(c) IAR

IAR consists of cutback bitumen and granular aggregates with the minimum 80% crushed particles. The mixture contains 4.5% to 6.0% cutback bitumen by weight of mixed material. This material is used at temperatures below 0°C, remaining flexible and cohesive up to -10°C (ProPatch Specification Sheet). As reported in Table 4-3, this mixture contains open graded granular aggregates with a larger gradation range compared to QPR.

(c) HMA

HMA was produced according to the City of Edmonton gradation specifications for pothole patching. Granular aggregates gradation is presented in Table 4-3. Bitumen type is classified as PG 64-58; the weight of total mix is 5% and total air void of compacted mixture is 4%.

Table 4-3: Sieve analysis results of granular aggregate for CCM, HMA, QPR and IAR

CCM		HMA		QPR		IAR	
Sieve size (mm)	Percent passing	Sieve size (mm)	Percent passing	Sieve size (mm)	Percent passing	Sieve size (mm)	Percent passing
12.50	100	16.00	100	9.50	100	9.50	100
5.00	60 – 80	12.50	97.4	4.75	20 – 85	4.75	20 – 100
0.16	9 – 14	10.00	89.1	2.36	2 – 30	2.36	1 – 60
0.08	4 – 7	5.00	55.4	1.18	0 – 10	1.18	0 – 50

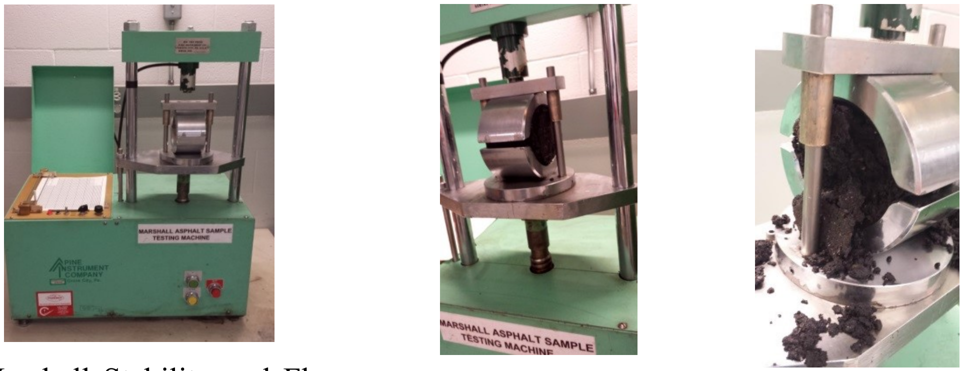
	2.50	37.4	0.75	0 – 6	0.30	0 – 20
	1.25	29.4	0.08	0 – 2	0.08	0 – 5
	0.63	24.7				
	0.32	18.1				
	0.16	11.4				
	0.08	6.8				

4.4.2. Marshall Stability testing

Stability of a patching mixture is one of the most important properties for preventing deformation caused by traffic; lack of stability results in fatigue cracking and shoving. Stability of a mixture depends on the material properties such as gradation and type of aggregate. Furthermore, proper compaction increases stability of patch by developing aggregate interlock. The Marshall stability test was performed by the Civil and Environmental Engineering Department, Rutgers University according to ASTM D 1559, where samples were aged before compaction to represent the actual traffic loading of several months (Maher *et al.* 2001).

In this study, the Marshall stability test was conducted following the ASTM 6927 – 06 standard procedures. Although this method is used for testing dense graded bituminous mixtures prepared with asphalt cement, Tetra Tech EBA has recently proposed a modified method for testing cold mix asphalt materials. A curing stage has been added with this standard procedure to accelerate the real field curing time, which is normally several weeks for emulsified and cutback bitumen. However, this test was performed in two different temperatures: 65°C and 135°C. In total, six samples were prepared for each mixture: three samples at 65°C and another three samples at 135°C. For each sample, approximately 1,200 grams loose mixtures were needed. At the beginning, the materials, along with 100-mm diameter molds, were cured in certain temperatures for 14 to 18 hours. After curing, materials were compacted using 75 blows on each face with a standard Marshall Hammer. The samples (65-mm height) were extruded from the mold after cooling down to room temperature. Bulk specific gravity of the samples was calculated by weighing the samples in air, water, and saturated surface dry conditions.

After that, the samples were put in the 60°C water bath for 30 minutes and then tested using the Marshall testing machine. A stability (lb) versus flow value (0.01 inch) graph was obtained for each test. The Marshall stability was recorded from the peak value of the graphs. Height correlation factor of each sample was applied on the stability value. Figure 4-1 represents the procedure of Marshall Stability and flow test.



(a) Marshall Stability and Flow test apparatus

(b) Loading of sample

(c) Failed sample

Figure 4-1: Marshall Stability and flow test procedure

Test result:

Marshall Stability is measured by the maximum load the material can stand before failure. It is related to the internal cohesion of the material (Maher *et al.* 2001). Figure 4-2 shows the results of the Marshall Stability test. As expected, Marshall Stability of the tested cold mix materials cured at 135°C exceeded the value of that cured at 65°C. Although dense graded CCM cured at 65°C had a low stability, open graded mixes of QPR and IAR demonstrated no strength and collapsed before testing. Also, at higher curing temperatures, dense graded CCM had the highest stability among the cold mixes and it was comparable to HMA. However, each set of samples' standard deviations of Marshall Stability results were not more than 12% at 135°C and not more than 13% at 65°C than that of the mean values.

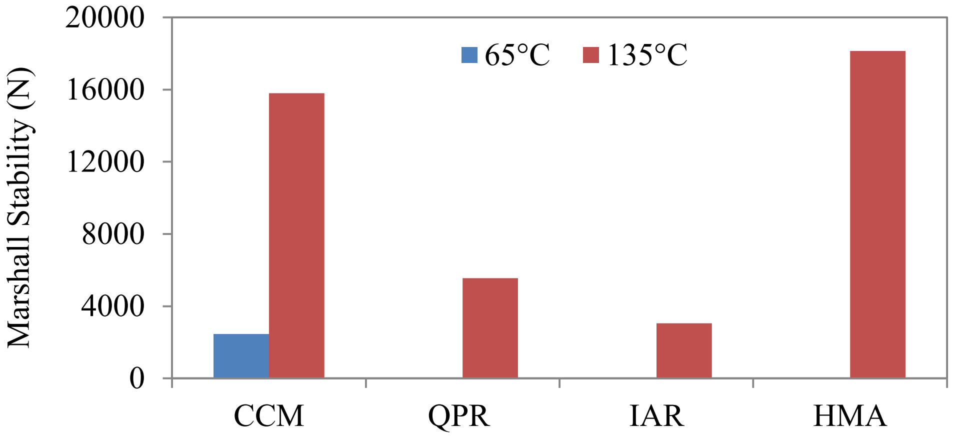


Figure 4-2: Marshall Stability of different patching materials

4.4.3. Indirect tensile strength testing

Indirect tensile strength (ITS) test is conducted to investigate moisture damage potential of patching material. Durability of patching mixture largely depends on the freeze-thaw resistance of the material, especially in cold regions where development of potholes as well as failure of repaired patches is caused by freeze-thaw cycles. Freeze-thaw resistance of patching material was determined by measuring ITS before and after freeze-thaw cycles and calculating the tensile strength ratio (TSR) following ASTM D4867 (Dong and Huang 2013).

In this study, ITS testing was performed following the AASHTO T 283-14 guidelines to measure the strength and moisture susceptibility of the cold asphalt mixtures. According to this standard, the long-term stripping susceptibility of a mixture is measured by determining the change of tensile strength of a specimen subjected to water saturation and accelerated water conditioning with a freeze-thaw cycle, then comparing it with similar properties of a dry specimen. Three sets of test specimens were prepared for each type of material. One set was tested for ITS in dry conditions. Another set was tested in saturated conditions. The third set was conditioned with a freeze-thaw cycle followed by a warm water soaking cycle before being tested for ITS. For sample preparation, cold asphalt mixes as well as Marshall Molds were cured at 135°C for 14 to 18 hours in order to simulate field curing of asphalt after several months. After curing, mixtures were placed into 100-mm (4-inch) diameter Marshall Molds and compacted with a Marshall Hammer for 75 blows on each side in order to prepare approximately 65-mm (2.5-inch) thick samples. This compaction simulates the actual field compaction of repeated wheel loads. The sample was then extruded when the compacted mold become cold. The air contents of the mixtures have been measured and found as 6.2%, 8.1%, 8.8% and 4.4% for CCM, QPR, IAR and HMA, respectively.

Dry samples were placed in the Universal Testing Machine (UTM) with a special loading frame with 50 mm/minute displacement rate. Maximum compressive strength of each specimen was recorded from the test. ITS of the samples was calculated using Equation 1.

$$S_t = 2000P/(\pi t D) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Equation 1}$$

Where,

S_t = tensile strength in kPa

P = maximum load in N

t = specimen thickness in mm

D = specimen diameter in mm

Second set of samples was soaked in a water bath at room temperature (25°C) for 24 hours to reach the degree of saturation between 70% and 80%. After saturation, the samples were tested following a similar procedure with the UTM, and the values of indirect tensile strength were calculated. These saturated tensile strength values are used to determine the TSR that shows the effect of water on the material.

To simulate freeze-thaw conditions, a third set of samples was soaked in water, wrapped in an airtight plastic bag and then placed in the freezer at –18°C for a minimum of 16 hours. Afterwards, the samples were transferred to the water bath at 60°C for 24 hours. The water bath temperature was then reduced from 60°C to 25°C within 15 minutes and left for two more hours. After calculating the ITS value for all the samples, TSR, the ratio of the tensile strength of saturated or conditioned samples to that of dry samples, was calculated according to Equation 2. TSR is an indicator of the effects of moisture and freeze-thaw cycle on the samples' strengths. According to the AASHTO T 283-14 guidelines specification, the minimum TSR value for asphalt mixes should be 0.8.

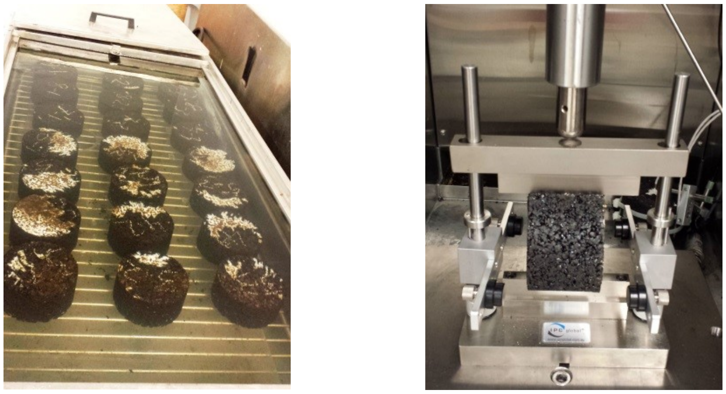
$TSR = S_2/S_1$ ……………………… Equation 2

Where,

S_1 = tensile strength of the dry sample in kPa

S_2 = tensile strength of the saturated or conditioned sample in kPa

Figure 4-3 represents the test procedure of the moisture susceptibility test.

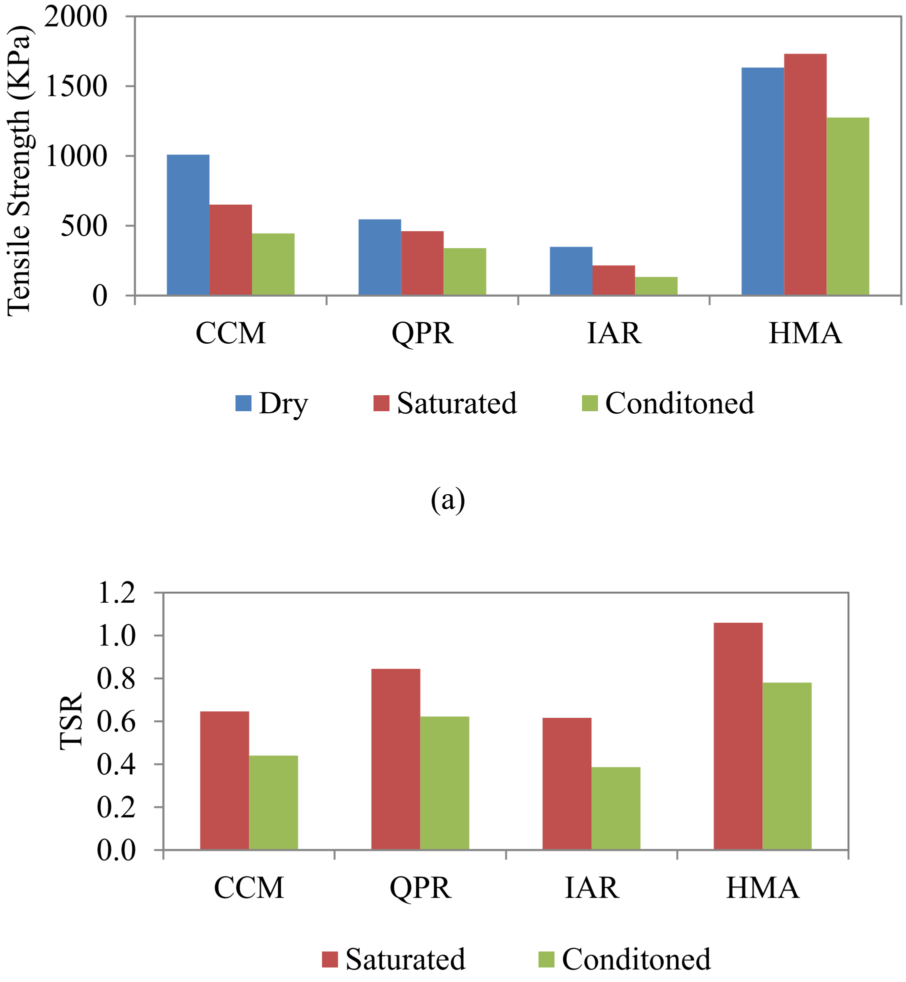


(a) Sample in water bath (b) Loading of sample

Figure 4-3: Moisture susceptibility test procedure

Test results:

Moisture susceptibility of cold patching materials is measured by tensile strength and TSR. Figure 4-4 summarises the results of the ITS test. According to Figure 4-4 (a), the highest tensile strength has been found for HMA, followed by CCM, QPR, and IAR. Tensile strength of the saturated sample was higher than that of the conditioned sample for all tested patching mixtures. Figure 4-4 (b) represents the TSR of patching materials for both of the saturated and conditioned samples. TSR values of HMA have been found greater than 0.8 for both sample sets. TSR values for the water saturated samples of QPR mixture were greater than 0.8; however, they decreased to 0.6 after a freeze-thaw cycle. Comparatively lower TSR has been found for CCM and IAR for both of the saturated and conditioned samples. However, each set of samples' standard deviations of tensile strength values were not more than 10% than that of the mean values for dry and conditioned, but up to 20% variation in results were noticed for IAR at saturated conditions.



(a)

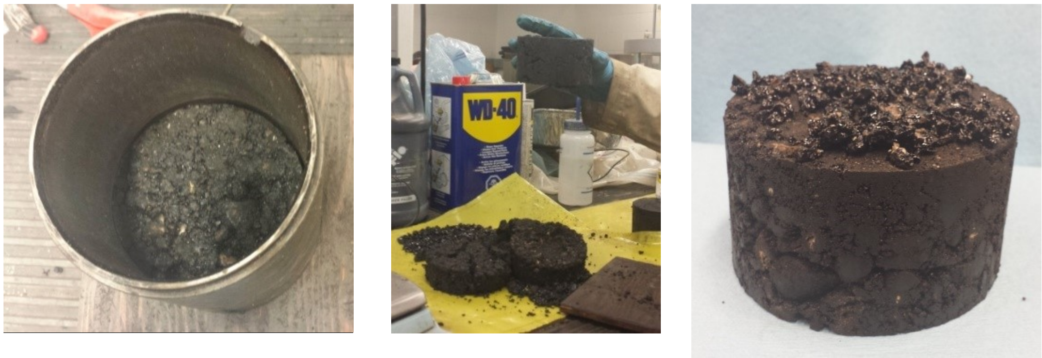
(b)

Figure 4-4: (a) Tensile strength and (b) TSR of different materials

4.4.4. Adhesiveness testing

Adhesiveness test was conducted to investigate the bonding strength of patching materials within the existing pavement surface and the pothole sides. Edge disintegration and missing patches are results of inadequate adhesion. However, it becomes very important to check the adhesiveness property of the patching mixture in order to ensure a better performance of repaired patches.

An adhesiveness test was conducted following a test procedure used by the Virginia DOT (Dong and Huang 2013). Greater adhesiveness is attributed to materials with longer adhesion time or higher weight of remnant. A sample was prepared by placing 500 gm of loose mixture on top of the HMA sample (75-mm height) in a 100-mm diameter Marshall Mold and compacted with 10 blows of a Marshall Hammer at room temperature (25°C). The samples were then extruded and inverted until the specimen separated from the HMA surface. Time taken by the mixture to drop from the HMA is measured and recorded as the adhesion time of the material. Material attached to the surface of the HMA sample was weighed and reported as the weight of the remnant. For cold mixes, optimum adhesion time has been recommended as 5 to 30 seconds (Prowell and Franklin 1996). Figure 4-5 represents the procedure of the adhesion test.



(a) HMA at the bottom of Marshall mold

(b) Measuring adhesion time

(c) Remnant on top of HMA

Figure 4-5: Adhesion test procedure

Test results:

Adhesiveness of a material is measured by the adhesion time and weight of remnant. Figure 4-6 shows the results of the adhesiveness test. According to Figure 4-6 (a), adhesion time of CCM has been found within the acceptable range. Reported adhesion time of QPR and IAR is less than 5 seconds. As Figure 4-6 (b) demonstrates, the weight of remnant is higher for QPR and IAR. Relatively lower weight of remnant has been found for CMM. This result shows that IAR and QPR adhesion to HMA is better than CCM. Thus, all three of the cold mixes are recognized as appropriate adhesive material.

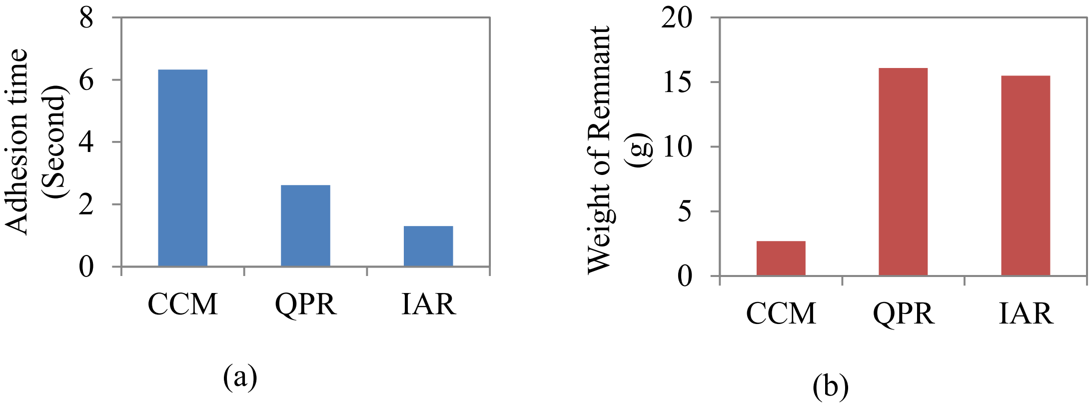


Figure 4-6: (a) Adhesion time and (b) Measure of remnant weight of different cold patching materials

4.4.5. Cohesion testing

Cohesion is defined as the bonding inside the patching material. Lack of cohesion causes raveling and missing patch distresses in the repaired patch. This test was developed by the Ontario Ministry of Transportation (MOT) to evaluate the cohesion and durability of stockpiled patching materials (Maher *et al.* 2001).

This study measured the cohesion of cold patching materials at temperatures of 4°C and 25°C. For preparing the samples at 25°C, 1,000 grams of loose cold mixes were placed into the Marshall Mold of 100-mm diameter and compacted by a Marshall Hammer using 15 blows on each side. After compaction, the sample was extruded and placed in a 30.5-cm diameter full-height sieve with 25.4-mm (1-inch) square openings. The sieve was then covered and rolled back and forth approximately 550 mm (22 inches) for 20 cycles. Test time was recommended as 20 seconds (Dong and Huang 2013). The loose materials were allowed to drop down by remaining in the sieve in the same position for 10 seconds. The retained material was then weighed to calculate the percentage of material retained following the formula as below.

Percentage of material retained = $[R/W_o] \times 100\%$ …………..Equation 3

Where,

W_o = initial weight of sample in grams

R = weight of retained material on 25.4 mm (1 inch) sieve in grams

For the other testing temperature, the loose material was placed in an environmental chamber at 4°C for 12 hours. After that, the samples were tested following a similar procedure. A higher percentage of retained material indicated a higher cohesiveness value. The minimum retained value is 60% according to the Ontario MOT (Dong and Huang 2013). Figure 4-7 represents the procedure of cohesion test.

(a) Sample on sieve before testing

(b) Retained material after testing

Figure 4-7: Cohesion test procedure

Test results:

Cohesion of a cold patching mixture is measured by the percentage of material retained on the sieve. A higher percentage of retained material indicates a more cohesive material. Figure 4-8 shows the value of retained material of different patching mixtures at two different temperatures. According to this figure, a similar percentage of retained material is observed for CCM and QPR at 4°C. IAR demonstrated the lowest material retaining percentage (almost 0%) at both 4°C and 25°C that could result in raveling and missing patches in the field. A higher percentage of material retained was observed for CCM at 25°C, followed by QPR.

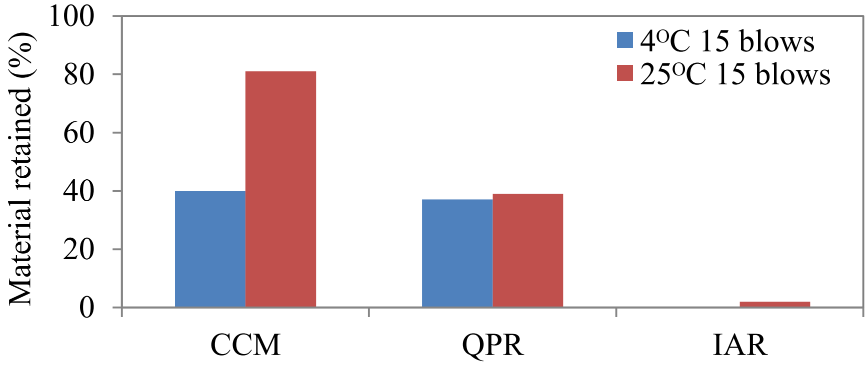


Figure 4-8: Value of retained material for different cold mixes

4.5. Discussion

As revealed by the survey responses, QPR is the most commonly used winter pothole patching material in Alberta and New Brunswick, and the ‘throw-and-go’ method is the most used pothole winter maintenance method in all provinces. The survival period of repaired patches in winter in Alberta and New Brunswick has been found not greater than three months. Besides, QPR is also used in Saskatchewan for all seasons, where a better durability of repaired patch is observed in the winter season. The laboratory test results showed that QPR has no stability before and after curing, and its strength is considerably lower than HMA. In addition, freeze-thaw cycles have a significant effect on QPR moisture damage. Adhesiveness of this material was appropriate, while cohesion values have been found as inadequate. Thus, using QPR for winter repairs may cause cracking, raveling, shoving and missing patch distresses with the shortened survival period of the repaired patch. Possible reasons for the extended survival period of the summer repaired patch include using the spray patch method in Alberta and HMA in New Brunswick. Additionally, higher summer temperatures also lead to better curing of the mixture.

CCM is used for repairing the major portion of potholes in Ontario and Quebec. The repaired patches in winter survive three to nine months with the ‘throw-and-go’ method. Laboratory test results indicated that the stability of CCM is low before curing; however, it reaches its appropriate values after curing is completed. CCM is more susceptible to moisture damage compared to QPR. Adhesiveness of this mixture was appropriate, cohesion was sufficient at higher temperatures and poor at lower temperatures. Hence, using CCM for winter repair may cause raveling and missing patch distresses.

QPR and IAR are used for winter as well as summer pothole repair in Manitoba. As indicated by the laboratory test results, IAR demonstrates no stability before curing and low strength after curing. Moisture susceptibility test results indicate that this material is sensitive to moisture and is greatly affected by freeze-thaw cycles. The indirect tensile strength for the dry sample is also lower than that of all the other tested materials. Moreover, it does not have any cohesion at room temperature and lower. Thus, using IAR for winter repair may cause cracking, raveling, shoving, edge disintegration and missing patch distresses, all of which can shorten the durability of the repaired patch. However, the winter survival period of a repaired patch has been found as more than nine months in Manitoba, and it exceeds two years for a summer-repaired patch.

4.6. Conclusions

This study discussed pothole repair in Canada based on questionnaire survey responses received from the six largest cold provinces. A laboratory study was conducted to measure the performance of patching materials used in these provinces. The following are conclusions based on the survey output and laboratory test results:

1 The questionnaire results indicated that CCM, QPR, IAR and HMA are widely used materials and the ‘throw-and-go’ is the most commonly used method for pothole patching procedure in six provinces in Canada.

2 In regards to the durability of different patching strategies, the maximum winter patch survival period is less than one year while summer patch can survive from one to more than two years.

3 It was observed that the durability of a repaired summer patch is higher with a combination of QPR and HMA and ‘throw-and-go’ as the patching method for QPR.

4 CCM showed the best strength between cold mixes and its Marshall stability was comparable to HMA after curing, which could be related to its dense gradation.

5 ITS results showed that between the three tested cold mixes, QPR had the best resistance to moisture; however, the freeze-thaw cycle increased its moisture sensitivity significantly.

6 CCM proved to have the best cohesion properties between all three cold mixes, followed by QPR and IAR. IAR showed no cohesion in both testing temperatures.

7 Laboratory test results indicated that curing time is a major factor for cold mixes to gain their strength. Survey results demonstrated shorter winter survival periods for all cold mixes that could be related to lack of sufficient curing, strength loss due to freeze-thaw cycles and inappropriate cohesion properties of cold mixes, as well as using the 'throw-and-go' patching method.

8 Comparison between different survival periods showed that, except for Manitoba, the best results for winter maintenance were achieved using HMA with the semi-permanent method and CCM with the 'throw-and-go' method. However, using a cold mix with less curing time, better cohesion properties and lower sensitivity to freeze-thaw cycles may increase durability of pothole patches, especially in winter time.

Chapter 5. Summary and Conclusion

5.1. Summary

Potholes are one of the most severe and concerning asphalt pavement distresses in regions with cold and wet winters. The service life and performance level of a pavement structure is significantly decreased by the formation of potholes. Patching of potholes is an important form of flexible pavement maintenance performed by most of the transportation agencies. Effectiveness of patching strategy largely depends on quality of patching mixture, repair procedure and period of patching.

A number of research studies were conducted on pothole repairs throughout the past three decades. The previous research focused on performance evaluation of pothole repair materials, methods and long-term cost-effective repair procedures based on field investigation; quality assurance of cold patching materials throughout laboratory testing; and determining the most common patching materials, methods and equipment used by transportation agencies around two states of the United States and Europe through a questionnaire survey. From previous research field investigation data, ‘throw-and-go’ and spray injection were found to be more productive methods, while the semi-permanent method was observed to be more cost-effective on a long-term basis. Key findings of laboratory testing data depicted that properties of HMA are much higher than the cold mixes. The survey outcomes indicated that ‘throw-and go’ and spray injection are common patching methods according to previous research.

However, this thesis presented an extensive literature review on flexible pavement distresses, pothole types and their development, patching materials, repair procedure and post-patching distresses. Moreover, past research on pothole maintenance is also discussed in this study. To attain the main goal of this research, a questionnaire survey was conducted on pavement maintenance for potholes in cold climates. The questionnaire gathered information from six provincial transportation agencies in Canada regarding the present road network characteristics, pothole development factors, current repair techniques, available patching materials, durability of the repaired patch and common patch distresses. The importance and severity of the pothole problem and the effectiveness of the remedial measure for potholes in Canada were investigated from the survey outcome. Furthermore, the most influential factor of pothole formation was identified and analyzed based on the survey results. A laboratory testing program was also conducted to evaluate the performance of patching materials found to be most commonly used by the six provinces in Canada.

5.2. Conclusion

This thesis discussed the pothole problem and its maintenance in Canada based on questionnaire survey responses received from the six largest cold climate provinces. Additionally, a laboratory evaluation was conducted to measure the performance of used patching materials in these provinces. Based on the work carried out in this study, the following conclusions can be drawn.

1. A clear concept on the severity of the pothole problem has been found from the survey outcomes. About three fourths of total developed potholes are of moderate to high severity in the study area, and the provinces with poor road conditions have a higher percentage of moderate to high severity potholes.

2. The most important factor related to pothole formation was identified from the questionnaire as the freeze-thaw cycle. Moreover, traffic load, poor drainage and pavement age are also listed as important issues.

3. About 80% of total pothole patching operations are done in the summer period. CCM, HMA and two proprietary cold mixes (QPR and IAR) are used for winter as well as summer repairs.

4. Based on the research, the six provinces of Canada frequently use the ‘throw-and-go’ method for pothole repair operations in all seasons, and it covers about 84% of the total patching operations.

5. The overall information regarding the durability of different patching strategies established that the maximum winter patch survival period is one year while a summer patch can survive from one to more than two years.

6. The most concerning distresses of patch failures have been found as cracking, edge disintegration and raveling that resulted from inadequate stability, adhesion, cohesion and stripping potential in the patching material.

7. From the performance evaluation of patching materials in Canada, QPR and IAR were identified as less stable materials with inadequate adhesion and cohesion, while CCM was found as a patching material with higher stripping potential and poor cohesion.

8. From the laboratory test result, CCM showed the best strength and Marshall Stability between the cold mixes. Its stability after curing was comparable to HMA, which could be related to its dense gradation.

9. The best moisture resistance properties are observed in QPR from the ITS test results. Freeze and thaw cycle increased its moisture sensitivity significantly. However, all of the cold mixes were sensitive to freeze-thaw damage.

10. CCM proved to have the best cohesion properties between all three cold mixes, followed by QPR and IAR. IAR showed no cohesion in both testing temperatures.

11. Laboratory test results also indicated that temperature and curing time is a major factor for cold mixes to gain their strength. Survey results demonstrated shorter winter survival periods for all cold mixes, which could be related to lack of sufficient curing, strength loss due to freeze-thaw cycles, inappropriate cohesion properties of cold mixes and using the ‘throw-and-go’ patching method.

12. Comparison between different survival periods based on survey output showed that the best results for winter maintenance was achieved using HMA with the semi-permanent method and CCM with the ‘throw-and-go’ method. However, using a cold mix with less curing time, better cohesion properties and lower sensitivity to freeze-thaw cycles may increase durability of pothole patches, especially in winter time.

5.3. Future research

This study encountered several potential possibilities for future work on improving pothole repair strategies. These possibilities include the following.

In this study, a questionnaire survey was conducted to collect data regarding pothole maintenance from provincial transportation agencies in colder regions of Canada. This work can be considered an initial step towards data accumulation and analysis in this area of research. The limitation of this study was that the annual budget for pothole repair could not be obtained from the survey responses, although a part of the questionnaire inquired about the patching budget. For future work, the pothole patching budget needs to be investigated in order to determine the severity of the pothole problem compared to other pavement distresses. The next step should also be collecting information about the pothole problem and its maintenance practices from all other Canadian provinces, as well as cold cities, in order to investigate the distribution of potholes and determine the common practices of pothole maintenance operations more specifically.

Performance evaluation of the patching materials was studied in the laboratory through testing for stability, sensitivity to freeze-thaw damage, adhesiveness and cohesion. In addition, a loaded wheel test should be also conducted to measure the resistance of pothole patching materials to permanent deformation.

In addition to patching material, repair procedure has a significant effect on the durability and performance of a patch. A part of this research included material evaluation of patching mixtures that are commonly used in six provinces in Canada. For further study, field investigation of repaired patches using different combinations of materials and methods should be a major step for evaluation of patching techniques. Moreover, long-term cost-effectiveness of pothole patching strategies can be evaluated from field monitoring data.

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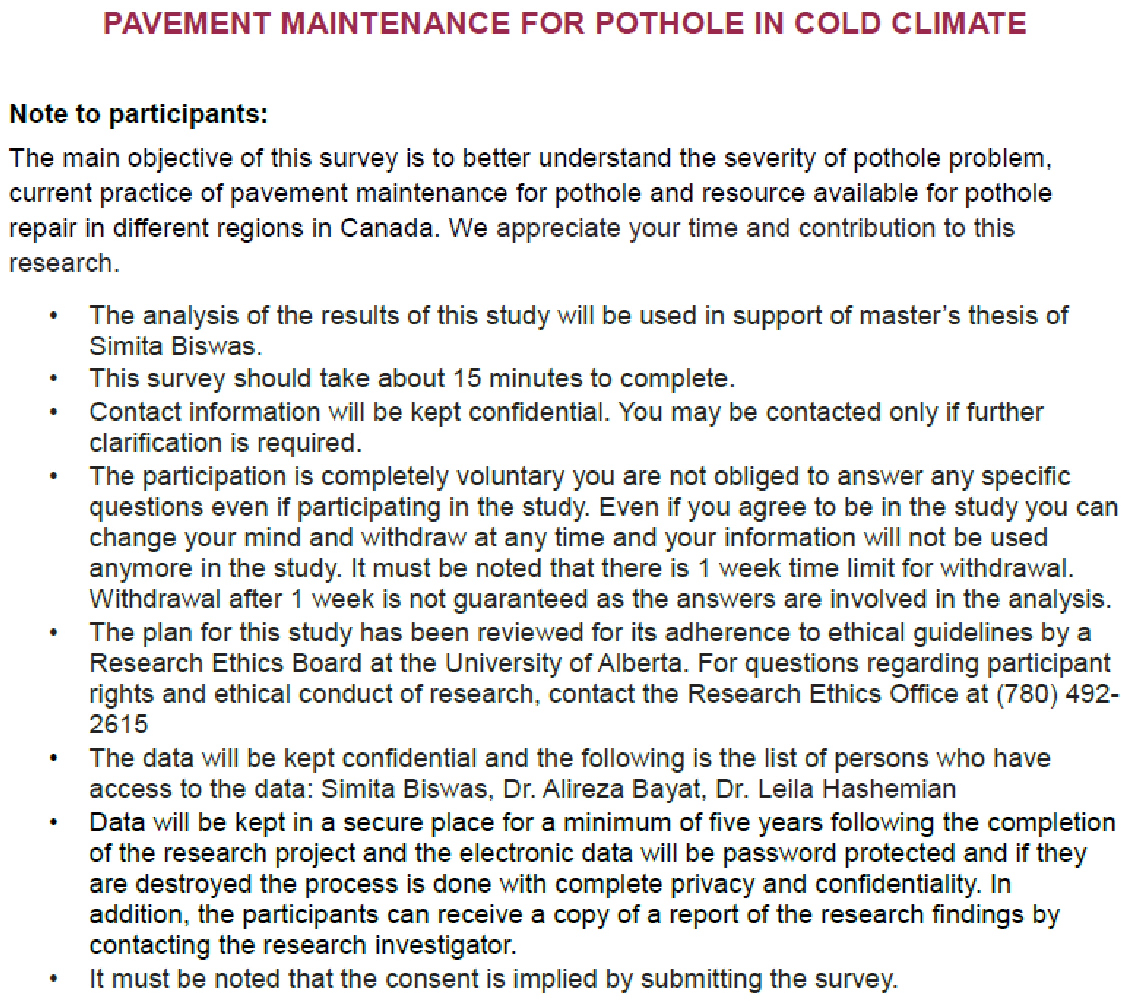
Appendix A

Questionnaire on ‘Pavement Maintenance for Pothole in Cold Climate’



PAVEMENT MAINTENANCE FOR POTHOLE IN COLD CLIMATE

Note to participants:

The main objective of this survey is to better understand the severity of pothole problem, current practice of pavement maintenance for pothole and resource available for pothole repair in different regions in Canada. We appreciate your time and contribution to this research.

- The analysis of the results of this study will be used in support of master’s thesis of Simita Biswas.
- This survey should take about 15 minutes to complete.
- Contact information will be kept confidential. You may be contacted only if further clarification is required.
- The participation is completely voluntary you are not obliged to answer any specific questions even if participating in the study. Even if you agree to be in the study you can change your mind and withdraw at any time and your information will not be used anymore in the study. It must be noted that there is 1 week time limit for withdrawal. Withdrawal after 1 week is not guaranteed as the answers are involved in the analysis.
- The plan for this study has been reviewed for its adherence to ethical guidelines by a Research Ethics Board at the University of Alberta. For questions regarding participant rights and ethical conduct of research, contact the Research Ethics Office at (780) 492-2615
- The data will be kept confidential and the following is the list of persons who have access to the data: Simita Biswas, Dr. Alireza Bayat, Dr. Leila Hashemian
- Data will be kept in a secure place for a minimum of five years following the completion of the research project and the electronic data will be password protected and if they are destroyed the process is done with complete privacy and confidentiality. In addition, the participants can receive a copy of a report of the research findings by contacting the research investigator.
- It must be noted that the consent is implied by submitting the survey.

GENERAL INFORMATION

Full Name:

Agency / Organization Name:

City, State/ Province:

Email:

Phone:

Specify your agency type:

- ○ Federal
- ○ Municipal
- ○ Provincial
- ○ County
- ○ Private Organization
- ○ Other, please specify:

NETWORK CHARACTERISTICS

Question 1: What is the network size (km and/ or lane-km) managed by your agency?

Answer:

Question 2: Please provide the AADT (Annual Average Daily Traffic), percentage of truck traffic and kilometre length for major arterial road in your agency's network.

AADT:

% of truck traffic:

Kilometre length:

Question 3: What are the present condition of different classes of road in your network according to PQI (Pavement Quality Index) or PSR (Present Serviceability Rating)?

Road types	Very good PQI (≤ 10.0) PSR (4-5)	Good PQI (≤ 8.5) PSR (3-4)	Fair PQI (≤ 7.0) PSR (2-3)	Poor PQI (≤ 5.0) PSR (1-2)	Very poor PQI (≤ 3.5) PSR (0-1)
Local road	○	○	○	○	○
Collector road	○	○	○	○	○
Minor arterial	○	○	○	○	○
Major arterial	○	○	○	○	○
Freeway	○	○	○	○	○
Other	○	○	○	○	○

Question 4: What are the pavement types in your network by percent?

Pavement types	Percentage
Flexible pavement	
Rigid pavement	
Other	

Question 5: Please provide the most common properties for following layers of flexible pavement for each type of road.

Road type	Asphalt thickness (mm)	Layer underneath the asphalt		
		Granular	Stabilized	Bitumenous
Local road		○	○	○
Collector road		○	○	○
Minor arterial		○	○	○
Major arterial		○	○	○
Freeway		○	○	○
Other		○	○	○

POTHOLE REPAIR

Question 6: What is the average annual number of potholes in the area under your agency?

Answer:

Question 7: On average, what percentage of potholes are repaired in winter and summer in your agency's network each year?

In winter (If applicable):

In summer:

Question 8: What is the severity of most of the potholes that are repaired by your agency each year? Please provide the percentage of repaired potholes in each category if available.

Low severity (depth < 25 mm) ○

Moderate severity (depth 25 - 50 mm) ○

High severity (depth > 50 mm) ○

Question 9: In your opinion, what are the probable causes of pothole development in your agency's network? Rate from 1 (least likely) to 5 (most likely).

Causes	1	2	3	4	5
Freeze-thaw cycles	○	○	○	○	○
Traffic load	○	○	○	○	○
Poor subgrade soil	○	○	○	○	○
Poor asphalt mixture	○	○	○	○	○
Poor drainage	○	○	○	○	○
Pavement age	○	○	○	○	○
High ground water table	○	○	○	○	○
High precipitation over the year	○	○	○	○	○
Inappropriate repair of pothole	○	○	○	○	○
Late rehabilitation of other distresses	○	○	○	○	○
Winter maintenance practice (snow removal)	○	○	○	○	○
Other, Please specify:	○	○	○	○	○

MATERIALS AND METHODS FOR POTHOLE REPAIR

Question 10: Which materials are used for pothole patching in winter? If more than one brand is used, then please specify the percentage of each.

Material	Percentage
☐ Local material	
☐ Conventional cold-mix	
☐ HMA (Hot Mix Asphalt)	
☐ QPR (Quality Pavement Repair)	
☐ UPM (Unique Paving Material)	
☐ IAR (Innovative Asphalt Repair)	
☐ Spray injection	
☐ Performix	
☐ SuitKote	
☐ Permapatch	
☐ WesPro	
☐ EZ-Street	
☐ Other, please specify:	

Question 11: Are the same materials used for pothole repair in summer?

○ Yes

○ No, please specify the materia

Question 12: Are the patch mixtures tested in the laboratory?

○ No

○ Yes, please specify the test:

Question 13: What methods are used for pothole repair in winter? Select all that apply. If more than one method is used, then please specify percentage of the total use.

Methods	Percentage of total use
☐ Throw and go	
☐ Semi-permanent	
☐ Spray injection	
☐ Edge-seal	
☐ Other, please specify	

Question 14: Are the same methods used for pothole repair in summer?

- ○ Yes
- ○ No, please specify the method

Question 15: What are the average survival periods of repaired patch in winter and summer?

In winter:	In summer:
○ < 3 months ○ 3 - 6 months ○ 6 - 9 months ○ 9 months - 1 year ○ 1 - 1.5 year ○ 1.5 - 2 year ○ > 2 year	○ < 3 months ○ 3 - 6 months ○ 6 - 9 months ○ 9 months - 1 year ○ 1 - 1.5 year ○ 1.5 - 2 year ○ > 2 year

Question 16: In your opinion, what types of distresses cause failure of repaired pothole (select all that apply) in your network? Rank from 1 (least common) to 5 (most common).

Distresses	1	2	3	4	5
☐ Cracking	○	○	○	○	○
☐ Bleeding	○	○	○	○	○
☐ Edge disintegration	○	○	○	○	○
☐ Missing patch	○	○	○	○	○
☐ Shoving	○	○	○	○	○
☐ Raveling	○	○	○	○	○
☐ Dishing	○	○	○	○	○
☐ Other, please specify:	○	○	○	○	○

PAVEMENT REPAIR BUDGET

Question 17: What is your agency's average annual pavement operating budget ($) over the last five years?

Answer:

Question 18: How much of the agency's annual pavement operating budget (percentage or $) is allocated to pothole repair?

Answer:

OTHERS

Question 19: What is the number of annual average pothole damage claims in your agency's area?

Answer:

Question 20: Please share your personal opinion regarding how future pothole repair can be improved (equipment, material, budget, etc.)

Appendix B

Investigation on seasonal variation of thermal induced strain in asphalt pavement based on field measurement and laboratory testing

Abstract

Structural response of flexible pavement is largely influenced by the variation of pavement temperature. Daily and seasonal fluctuation of temperature causes expansion and contraction of pavement material that leads to the generation of thermal strain. In this study, field observation and laboratory tests were conducted to investigate seasonal variation of thermal-induced strain in flexible pavement. Field observations were conducted at the Integrated Road Research Facility (IRRF)'s test road in Edmonton, Alberta, Canada, which is fully equipped with structural and environmental monitoring instruments. The main objective of the field study was to determine the variation of thermal-induced strain in fall and winter seasons. Test results indicated that thermal-induced strain in winter is 1.33 to 2.0 times greater than that of fall due to certain daily fluctuations of pavement temperature. A comparable result was observed from laboratory testing of asphalt samples. Moreover, a similar trend of temperature and thermal strain was noticed from field observation and laboratory testing.

Introduction

Thermal-induced stress is built up on asphalt concrete due to extreme temperatures on hot summer and cold winter days. Thermal cracking is the result of thermal-induced stress. It is one of the most serious distresses in flexible pavement, especially in regions where daily and seasonal temperature change is significant and rapid. Water infiltration through thermal cracking can accelerate the formation of other distresses, including stripping in the HMA layer and weakening of base and subgrade layers. Flexible pavement is affected by temperature change in two different ways: daily temperature variation and seasonal temperature variation. Change in structural response is the result of seasonal variation of temperature, and thermal expansion and contraction are the results of daily thermal cycles (Tarefder and Islam 2014). Thermal cracking consists of two major distresses: (a) thermal fatigue cracking and (b) low-temperature cracking. Thermal fatigue cracking is caused by repetition of thermal cycles that build up the HMA stress lower than material strength. Generation of irrecoverable deformation and fluctuation of material stress and strain also result in thermal fatigue cracking (Al-Qadi *et al.* 2005). On the other hand, a high rate of cooling in extreme cold weather causes low-temperature cracking when the tensile thermal stresses exceed the tensile strength of the HMA. Thermal distresses are defined by the thermal properties, such as Coefficient of Thermal Contraction (CTC) and Coefficient of Thermal Expansion (CTE). CTC and CTE are the fractional dimension changes due to unit change of temperature (Islam *et al.* 2014). Thermal expansion and contraction cause thermal stress and strain generation within the asphalt layer (Bayat *et al.* 2012). Therefore, it is vital to quantify and compare the asphalt strain amplitude associated with thermal loading on flexible pavements in fall and winter seasons as well as higher and lower temperature ranges.

Several studies have been conducted to evaluate the variation in thermal-induced strain of asphalt pavement through field experiments (Al-Qadi *et al.* 2005, Bayat *et al.* 2012, Islam and Tarefder 2013). Longitudinal strain at the bottom of the HMA was recorded as high as 350 μm/m from a one-year field experiment using Asphalt Strain Gauges (ASGs) at the Virginia Smart Road located in Southwest Virginia (Al-Qadi *et al.* 2005). Another field study was performed at the Center for Pavement and Transportation Technology (CPATT) test track in Waterloo, Ontario, Canada, and the result shows that high amplitude thermal-induced strain can occur in flexible pavements on a daily and seasonal basis. The daily thermal-induced strain was as high as 600 to 650 μm/m during warm weather months, while it is lower during cold months (Bayat *et al.* 2012). However, the effect of certain daily temperature changes on asphalt strain in different seasons was not estimated through the studies. Another field observation was performed at a test road on the I-40 interstate highway in New Mexico, United States. The test result revealed that the structural response of flexible pavement depends on the temperature variation of the day (Islam and Tarefder 2013). In a recent study on thermal properties of asphalt concrete, it was found that the change in thermal strain differs with temperature. Thus, a nonlinear relationship of thermal coefficients has been found with respect to temperature (Islam and Tarefder 2015). Moreover, some laboratory testing programs were conducted to determine the thermal properties of asphalt concrete under different conditions using

ASG and Linear Variable Differential Transformers (LVDT) (Mehta *et al.* 1999, Islam *et al.* 2014, Islam and Tarefder 2014). However, it is certain that the previous research investigated the mechanism of thermal fatigue cracking; measuring asphalt thermal strain at the bottom of HMA on a daily, seasonal and yearly basis; and determining thermal properties of asphalt concrete using laboratory testing. But the past studies have not evaluated the effect of seasonal temperature change on asphalt thermal strain generation and did not attempt to compare the asphalt thermal strain for different temperature ranges.

Objectives and scope

The main objective of this study is to evaluate the effect of seasonal temperature variation on the generation of thermal-induced strain in flexible pavement based on field observation and laboratory testing. The specific objectives are as below:

- Determining the variation of asphalt concrete thermal-induced strain in fall and winter seasons based on field observation.
- Investigating thermal-induced strain variation in different temperature ranges based on laboratory testing of an asphalt slab.
- Establishing a relationship between thermal-induced strain ratio for higher and lower temperatures based on laboratory testing of a cylindrical asphalt sample compared with that of field observation data.

Research methodology

In this study, thermal-induced strain was measured in three different methods presented in Figure 1. Method 1 is a field observation of five months' monitoring of a test road. Thermal-induced strain, air temperature and pavement temperature data were collected from the Integrated Road Research Facility (IRRF) test road and the strain variation in fall and winter seasons were measured and compared. In Method 2, an asphalt slab was prepared and tested in the laboratory to observe the thermal-induced strain variation within a certain temperature range. The temperature range was selected between 31°C to -34°C based on the maximum and minimum air temperature from January 2014 to January 2015 according to field monitoring data. In this method, strain was measured with ASG inserted into the asphalt slab. The ASG was tested previously in an environment chamber to determine its temperature dependency. Method 3 is a laboratory test of a cylindrical asphalt sample. Thermal strain due to small variations of temperature was observed in this test within a small temperature range between 20°C to -16°C. In this test, strain was measured with LVDTs.

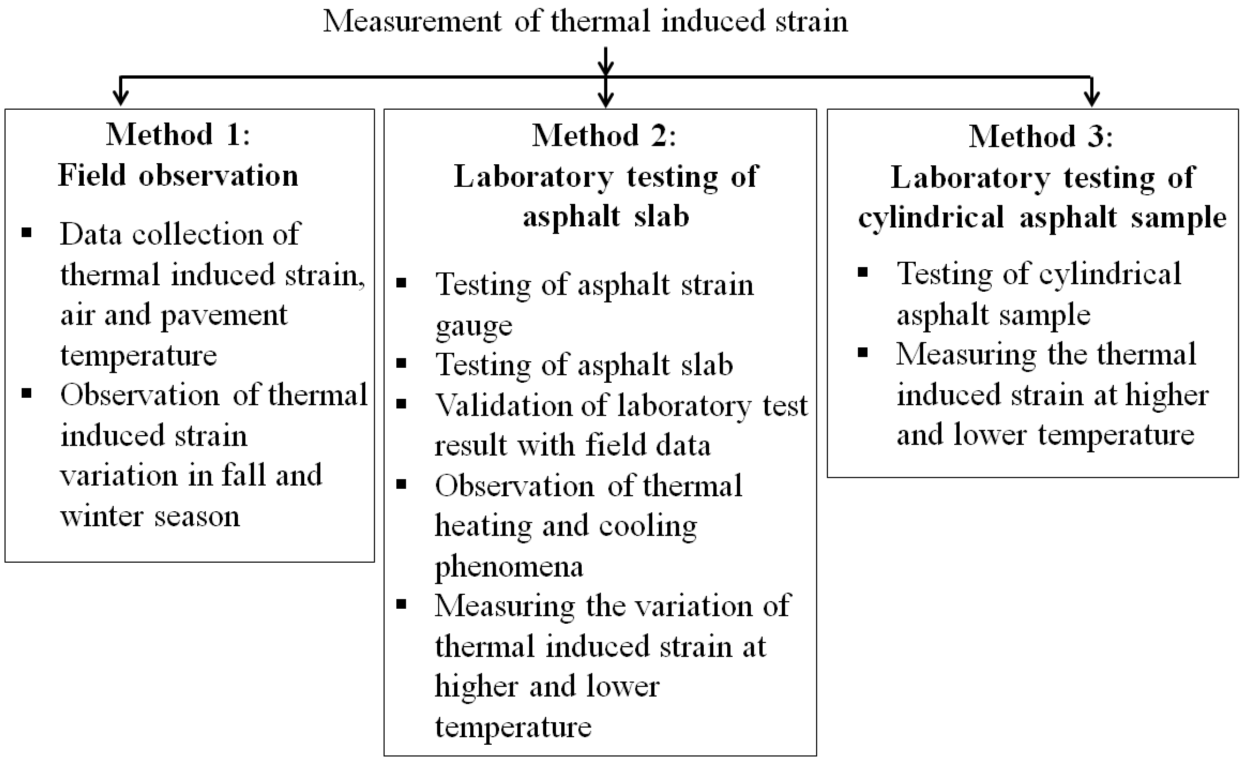


Figure 1: Schematics of the research methodology

Field observation

Instrumented section

Field observation of this study was conducted at the IRRF's test road in Edmonton, Alberta, Canada, at the Edmonton Waste Management Centre (EWMC), which is fully equipped with structural and environmental monitoring instruments. The structure of the flexible pavement consists of two types of HMA layers as wearing and binder courses placed on top of a granular base course (GBC) on a clayey sand (SC) subgrade. Figure 2 shows the pavement cross-section at the IRRF, and the fundamental physical properties of the binder and wearing layers are listed in Table 1.

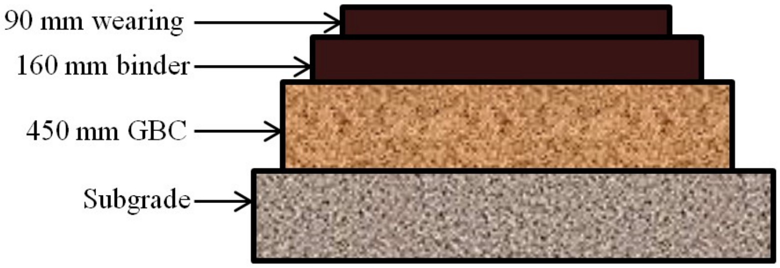


Figure 2: Cross-section of the IRRF test road

Table 1: Physical properties of wearing and binder layers

Property	Asphalt Physical Properties	
	Wearing	Binder
Max. Aggregate Size (mm)	12.5	25.0
Virgin Binder Grade	PG 58-28	PG 58-28
RAP Binder Grade	PG 70-28	PG 70-28
Blended Binder Grade	PG 58-28	PG 58-28
Percentage of Incorporated RAP (%)	20.0	10.0
Binder Content by Weight of Mix (%)	4.6	5.3
Void in Mineral Aggregate (VMA) (%)	13.1	14.3
Void Filled with Asphalt (VFA) (%)	69.4	74.9
Air Voids (%)	4.0	3.6
Density (kg/m³)	2355.0	2344.0
Marshal Stability (KN)	17.7	16.9
Flow (mm)	2.3	2.5
Theoretical Film Thickness (µm)	6.7	7.1
Tensile Strength Ratio (TSR) (%)	98.0	81.6

The plan view of the pavement monitoring control section is presented in Figure 3. ASGs were installed 250 mm deep in the HMA layer in three directions: six in the longitudinal (ASG-L), six in the transverse (ASG-T), and six in the vertical direction (ASG-V). ASG-Ls were installed parallel to the traffic direction, and transverse strain gauges were embedded perpendicular to the traffic direction. ASGs have two steel arms and middle AC material embedded inside a membrane. Expansion and contraction of the asphalt pavement occurs due to change in temperature. This phenomena causes increasing or shortening of steel arms, and thus the resulting strain is measured (Islam and Tarefder 2014). In addition to strain gauge, Earth Pressure Cells (EPC), Time Domain Reflectometers (TDR) and asphalt thermistors were placed within the structure for comprehensive data collection at the IRRF.

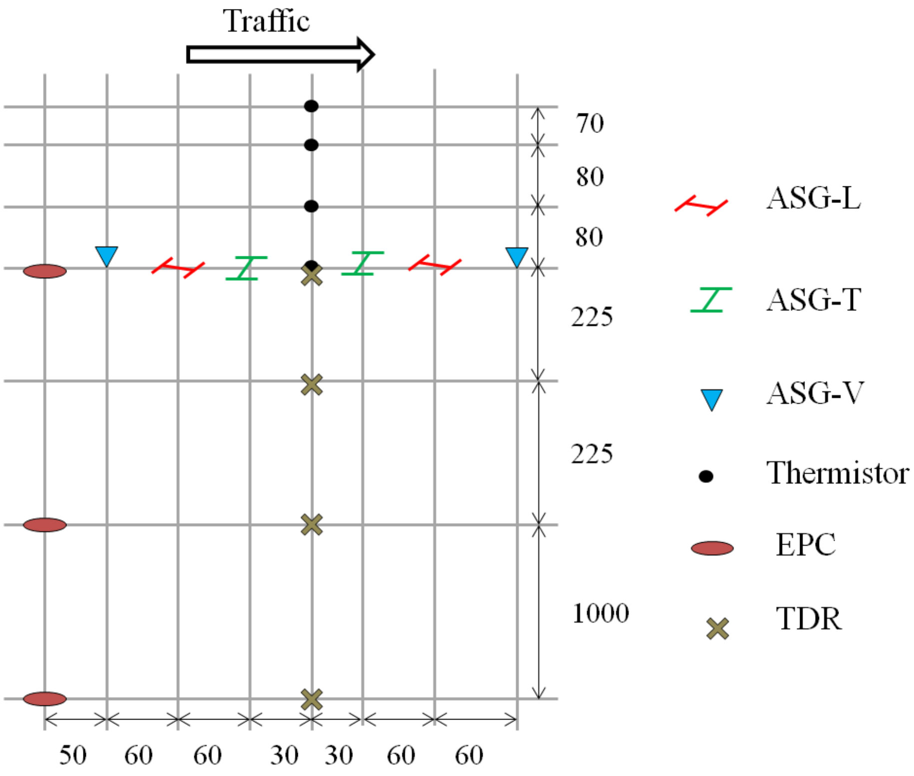


Figure 3: Plan view of the IRRF test section (all units are in mm)

Data collection and analysis

Thermal strain, ambient air temperature and pavement temperature data were collected for five months' monitoring period from August 11, 2014 to January 20, 2015 at the bottom of the HMA. Strain data was collected via a CR9000X datalogger at 15-min intervals in static mode and 0.002-s intervals in dynamic mode, and temperature data was recorded at 15-min intervals using a CR1000 datalogger. During this time period, the maximum and minimum daily average pavement temperature was recorded as 33.8°C and -13.5°C on August 11, 2014 and January 9, 2015, respectively, when the ambient air temperatures were recorded as 23.3°C and -21.4°C. Figure 4 illustrates the seasonal variation of thermal-induced longitudinal strain of ASG-L2, air and pavement temperature from August 11, 2014 to January 13, 2015 according to field measurements. All measured strain data were zeroed against the associated value recorded on August 11, 2014. A similar trend was noted for strain and temperature variations from this figure. Air temperature data shows more variation than pavement temperature data throughout the monitoring period. During the observation period, the maximum and minimum longitudinal strains were recorded as 200 µm/m and -684 µm/m on September 22, 2014 and January 11, 2015, respectively. At the end of the monitoring period, longitudinal strain did not return to the initial value and the irrecoverable longitudinal strain generation was -192 µm/m at the bottom of the HMA.

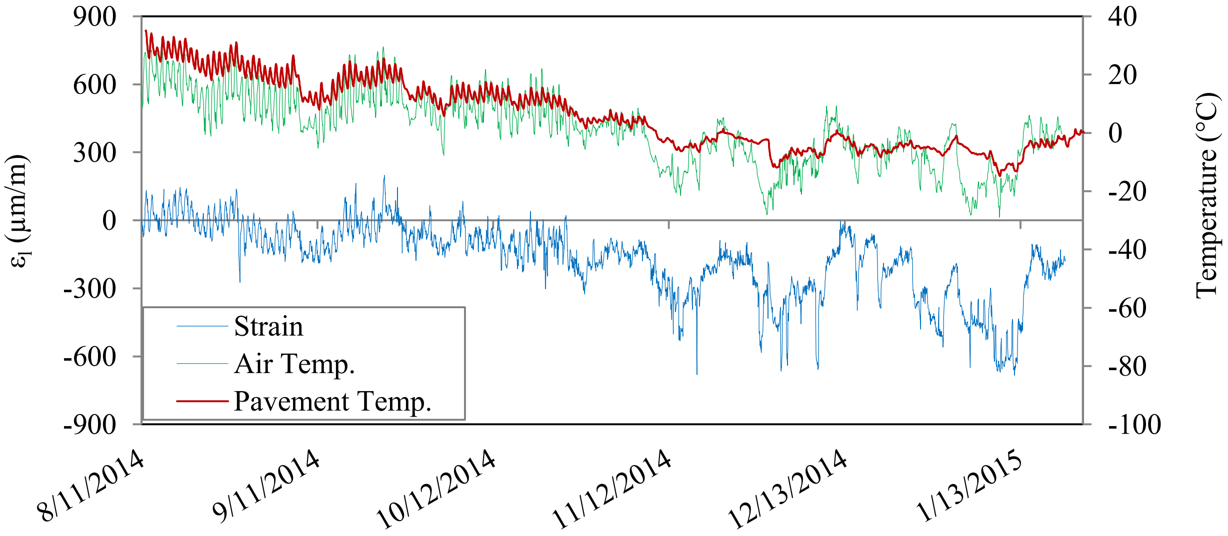


Figure 4: Seasonal variation of thermal-induced longitudinal strain of ASG-L2, air and pavement temperature according to field measurements

From the five months' field observation data, longitudinal strain generation due to similar daily pavement temperature variation in fall and winter seasons were measured and listed in Table 2. For evaluation purposes, the selected range of daily pavement temperature variation is from 2.5°C to 6°C. Pavement temperature varies from 11°C to 31°C in warmer months of fall and -2°C to -12.5°C in the cold season. It is obvious from Table 2 that thermal strain increases with an increase in temperature fluctuation during both the fall and winter season. From the recorded data, it was noted that the thermal strain generation is 1.4 to 2.0 times greater in winter compared to fall due to similar variation of daily pavement temperature. This result indicates that the effect of daily temperature fluctuation is different in two seasons and it is greater in winter than in fall.

Table 2: Variation of thermal-induced strain in fall and winter seasons according to field measurement

Daily pavement temperature variation (°C)	Range of pavement temperature (°C)		Thermal-induced strain (μm/m)		Ratio of strain
	Fall	Winter	Fall	Winter	
6	25 to 31	-8 to -2	177.13	250.27	1.41
5	25 to 30	-10 to -5	162.35	231.90	1.42
4.5	24 to 28.5	-12.5 to -8	123.16	227.94	1.85
3.5	27 to 30.5	-8.5 to -5	98.04	196.69	2.00
2.5	11 to 13.5	-6.5 to -4	67.61	128.26	1.90

Laboratory testing of asphalt slab

To determine the thermal strain of asphalt in certain temperature ranges, an asphalt slab was prepared and tested in the laboratory. ASG was inserted into the slab to measure the asphalt strain. Before preparing the asphalt slab, the ASG was tested with differential temperature to see the effect of temperature change in ASG. Testing of ASG and asphalt slab are described below.

Testing of asphalt strain gauge

The ASG M-86 with a calibration factor of 309.54μƐ/mvolt was used in this experiment. This strain gauge was previously installed in the IRRF test road for measuring asphalt strain in the field. The ASG and a thermistor were placed in an environmental chamber and connected with a datalogger to record the strain and temperature data in 10-s intervals. This test was conducted for three hours with differential temperature between -

12°C to 17°C. The recorded strain and temperature data is presented in Figure 5. The result specifies that the ASG was independent of temperature change.

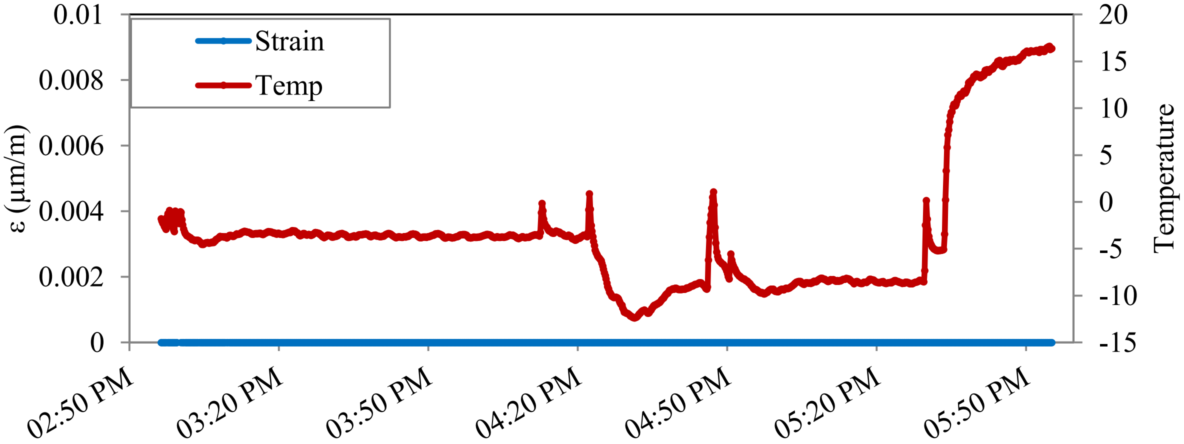


Figure 5: Variation of thermal strain of ASG with varying temperature

Laboratory testing of asphalt slab

Sample preparation

For preparing the asphalt slab, loose mixes of the IRRF test road were collected and heated at a temperature of 135°C for two hours. The gradation of the loose mix is presented in following figure.

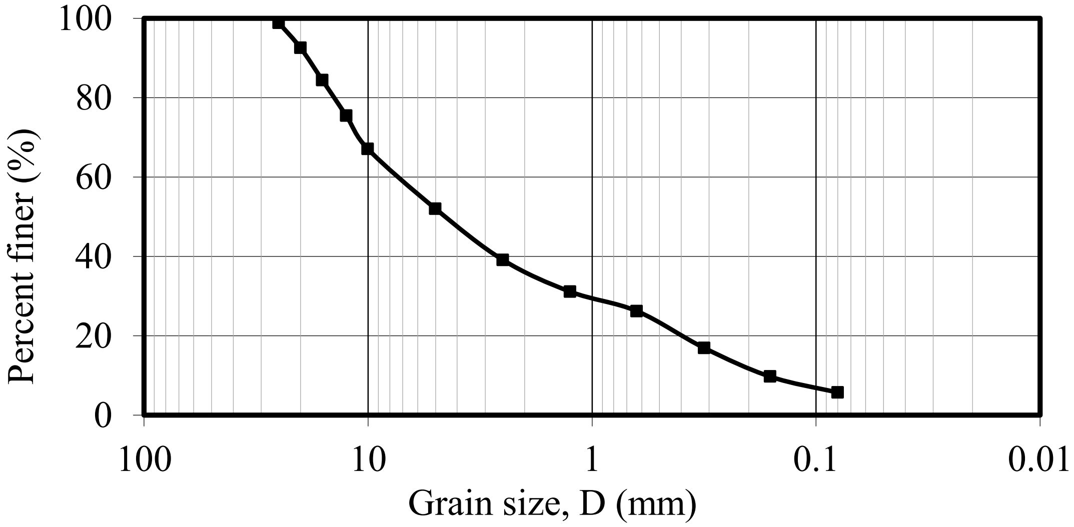
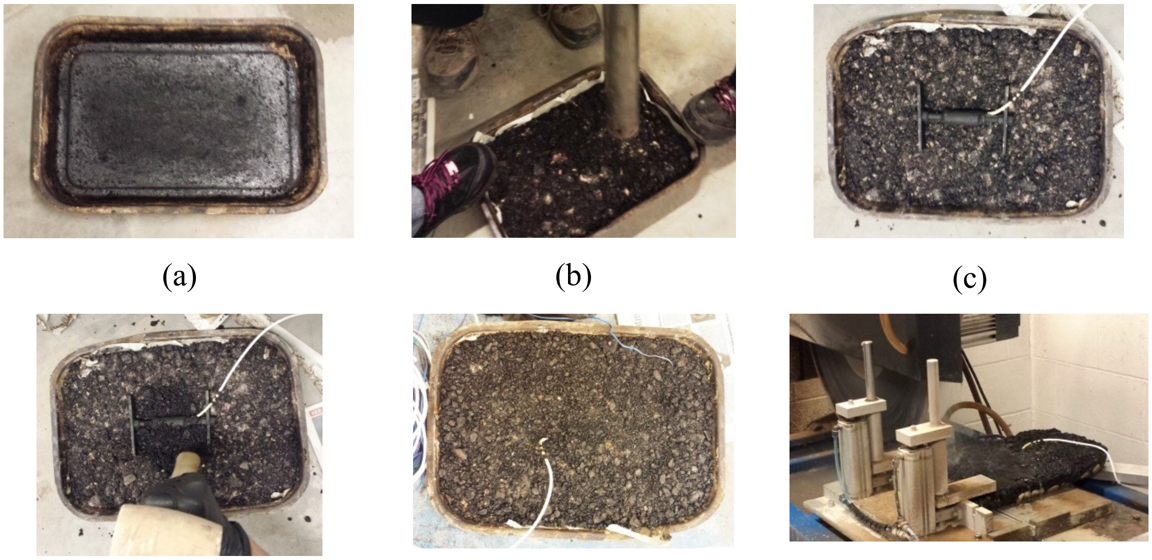


Figure 6: Gradation of loose mixture

After heating the asphalt mixture, half of the loose mixes were placed in a compaction tray with dimensions of 40 cm × 30 cm and compacted manually by a Marshall Hammer to prepare the first layer of asphalt slab. The ASG was then placed on top of the first layer, and the rest of asphalt mixes were placed and compacted carefully to prepare the second layer. A thermistor was installed on top of the second layer so it can measure the temperature at the bottom of the asphalt layer when the slab is inverted and placed on top of the base layer. The uneven edges of the asphalt slab were cut to make it smooth with final dimensions of 30 cm × 20 cm. After preparing the asphalt slab, another compaction tray with the same dimensions was filled with granular soil and compacted to prepare the base layer. On top of the compacted base layer, the asphalt slab was placed in a way so that the first compacted asphalt layer was in the upper direction. Before placing the asphalt slab, a thin layer of asphalt tack coat was applied on top of the base layer. When the sample was ready, it was placed in the environmental chamber, and the ASG and thermistor were connected with a datalogger to record the strain and temperature data respectively in 10-s intervals. The preparation procedure of asphalt slab is presented in Figure 7.



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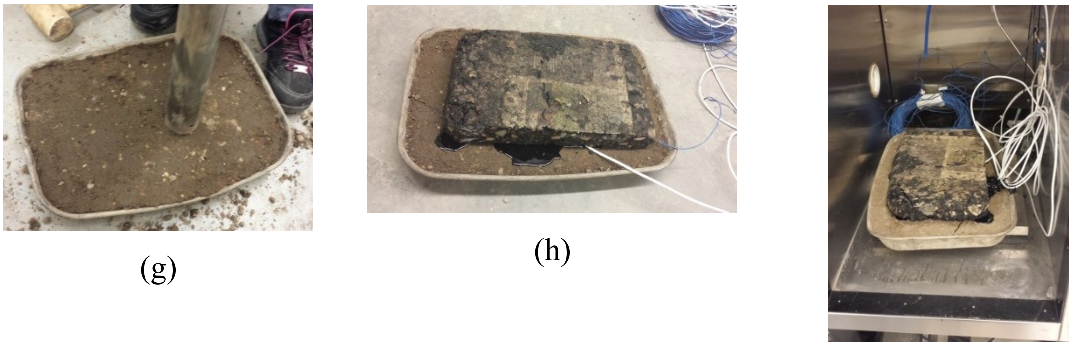


(g)

(h)

(i)

Figure 7: Preparation procedure of asphalt slab (a) compaction tray, (b) compaction of first layer, (c) placement of ASG, (d) compaction of second layer, (e) placement of thermistor, (f) cutting the edges of slab, (g) compaction of granular soil, (h) placing the asphalt slab on top of compacted soil, (i) sample in UTM

Testing

Thermal-induced strains were measured at the bottom of the HMA of an asphalt slab constructed on top of a base layer in the laboratory. Chamber temperature was controlled between 30°C and -40°C using the dynamic modulus environmental chamber. At the beginning of the testing, the chamber temperature was 25.8°C. The temperature of the environmental chamber was changed 10°C at a time interval of more than seven hours. The maximum and minimum temperatures recorded by the thermistor during this 10 days' monitoring period were 31°C and -34°C, respectively. The resulting deformation of the sample was measured with a datalogger. All measured strain data were zeroed against the associated value recorded for a temperature of 0°C. Figure 8 is the plot of thermal strain and temperature data during laboratory testing. From the figure, it is certain that thermal strain follows a similar trend with the temperature cycles. At the end of testing, the irrecoverable strain generation at 25.8°C temperature was approximately 82 μm/m.

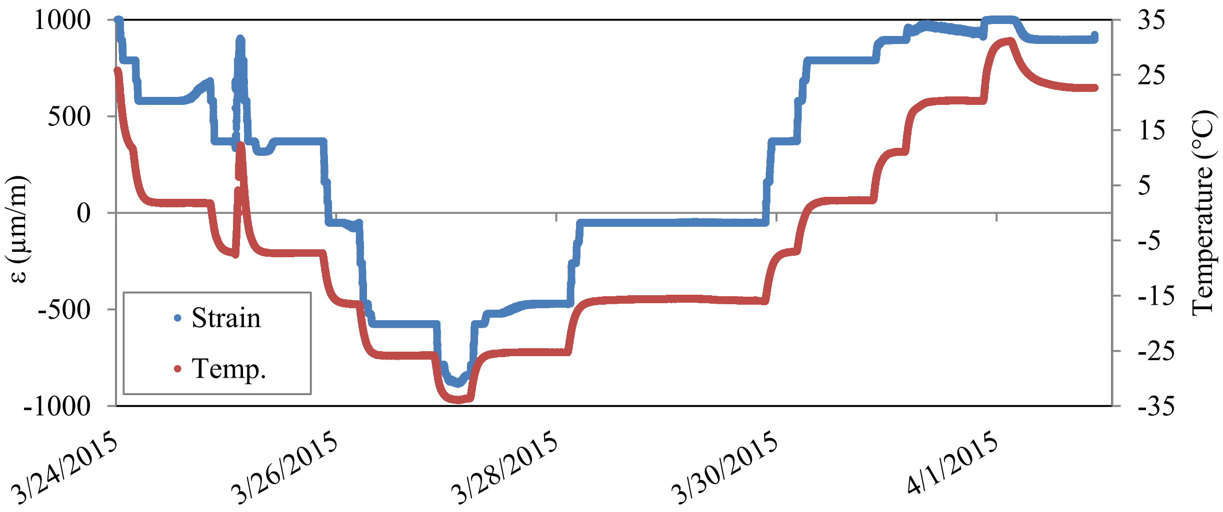


Figure 8: Variation of thermal strain of asphalt slab with varying temperature

For validation of the laboratory test results, the thermal strains from the laboratory test were compared with the field-measured longitudinal and transverse strain data for similar fluctuation of daily pavement temperature. The comparison between laboratory and field strain data are presented in Figure 9. In spite of having some fluctuation in strain, laboratory strain data is comparable to field longitudinal strain in most cases.

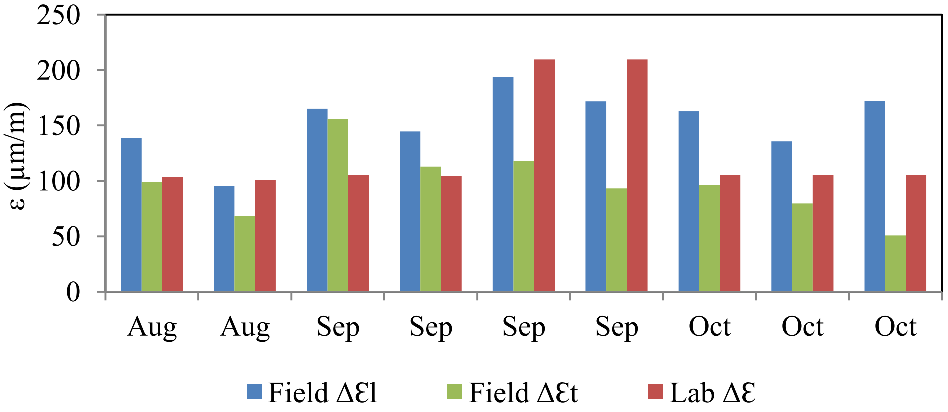


Figure 9: Comparison between laboratory and field strain data

Heating and cooling phenomena for a temperature range of -34°C to 31°C are represented in Figure 10. The heating curve coincides with the cooling line in lower temperatures from -7°C to -34°C, although a small difference in strain generation is observed at higher temperatures. Both heating and cooling lines are flatter at a higher temperature than that of a lower temperature due to similar ΔT. However, it has been observed that the strain generation is less at a higher temperature than at a lower temperature.

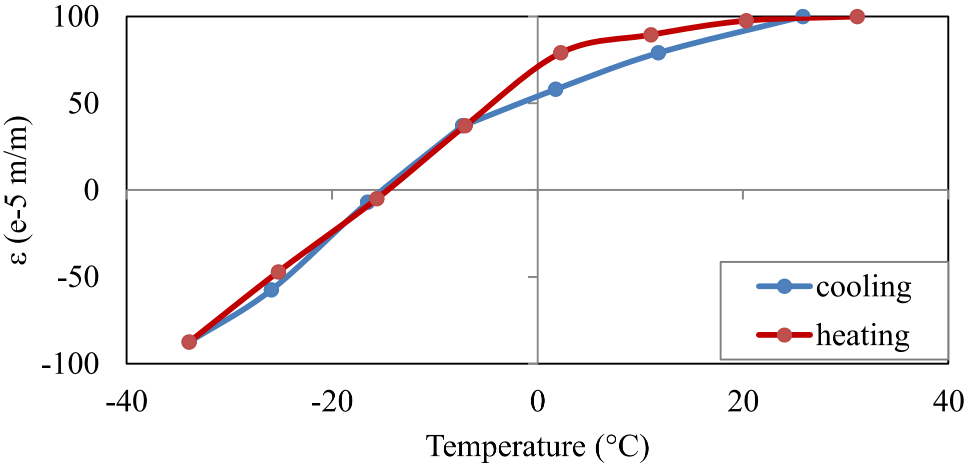


Figure 10: Variations of strain values upon cooling and heating

CTC and CTE are calculated for similar temperature ranges from the above test data and shown in Figure 11. At lower temperature, CTC and CTE have been found from 3.8 to 5.4, which indicates higher strain generation due to unit change in temperature. On the other hand, the coefficients are not more than 2.5 when the temperature is higher. These values also specify smaller strain creation due to unit change in temperature at high temperatures.

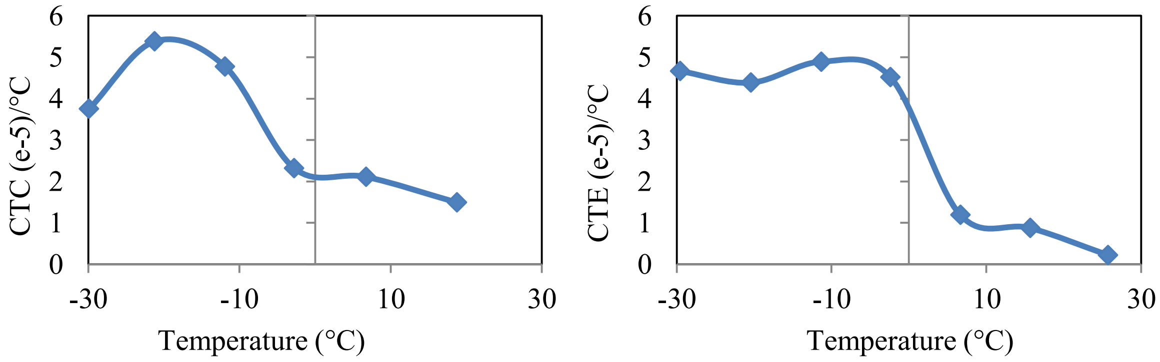


Figure 11: Coefficient of thermal contraction and expansion

Table 3 represents the thermal strain generation for different temperature ranges starting from 25.8°C to -34°C and again from -34°C to 31°C with a ΔT of 8°C to 14°C. The minimum and maximum thermal-induced strain generation was recorded as 81 and 504 μm/m for an approximate 9°C temperature change in a range of 11°C to 20°C and -26°C to -17°C, respectively. From the overall test result, 400 to 500 μm/m strain generation was noticed when the range of temperature is below 0°C and 80 to 210 μm/m when the range of temperature is above 0°C. This result is in agreement with thermal strain generation being greater at low temperatures and lesser at high temperatures.

Table 3: Variation of thermal-induced strain at higher and lower temperatures

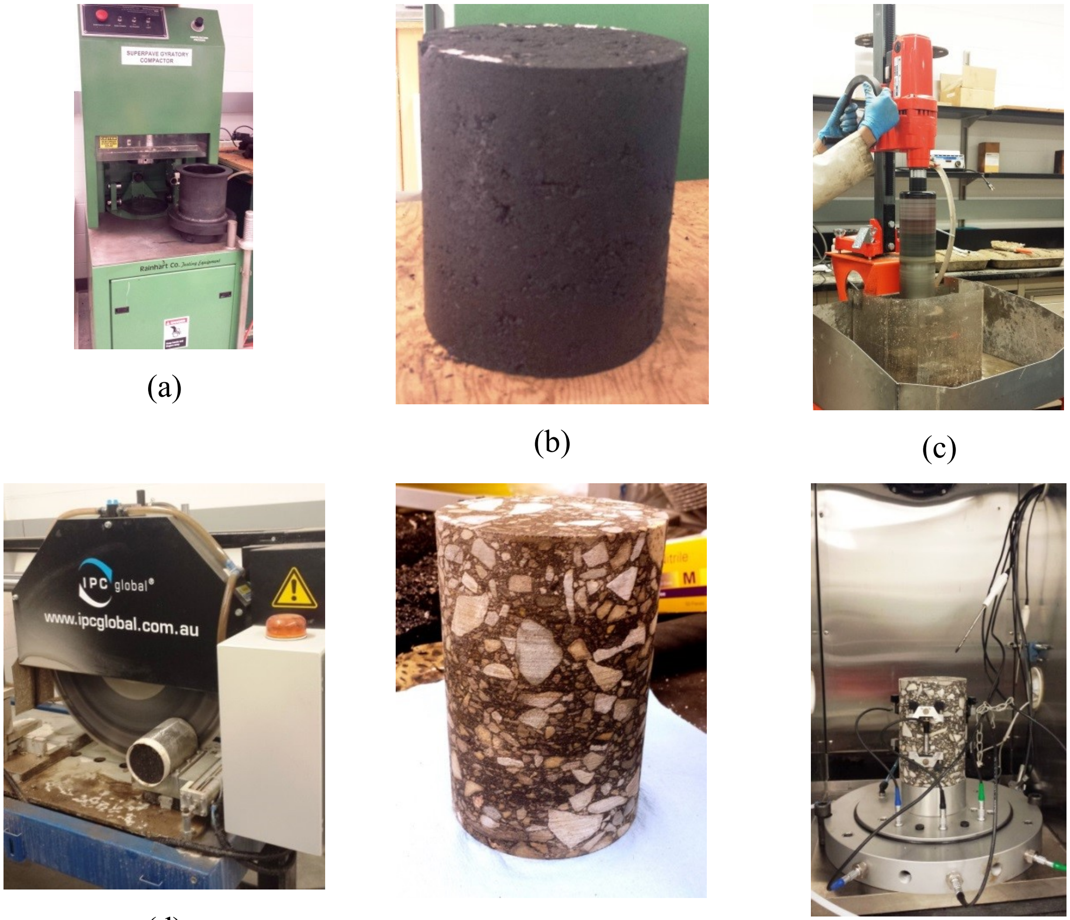
Change in temperature (°C)	Range of temperature (°C)	Thermal-induced strain (μm/m)
14.1	11.8 to 25.8	209.7
10.0	1.8 to 11.8	210.5
9.1	-7.3 to 1.8	209.7
9.2	-16.5 to -7.3	441.1
9.4	-25.9 to -16.5	503.8
8.0	-33.9 to -25.9	300.3
8.7	-33.9 to -25.2	404.0
9.6	-25.2 to -15.6	421.0
8.6	-15.6 to -7.0	420.2
9.3	-7.0 to 2.3	420.2
8.8	2.3 to 11.1	104.5
9.3	11.1 to 20.3	81.3
8.5	22.6 to 31.1	103.7

Laboratory testing of cylindrical sample

Sample preparation

Loose mixes of the IRRF test road were collected and heated at a temperature of 135°C for two hours in order to prepare the cylindrical asphalt sample. The loose sample was then placed in the Marshall mold and compacted with a superpave gyratory compactor, which is designed by the Strategic Highway Research Program (SHRP) according to

AASHTO PP 35-98 standard test compaction procedure for laboratory compaction of specimens (Solaimanian 1999). The size of the compacted sample was 15 cm diameter and 20 cm height. After extruding the compacted sample, it was cored and the edges were cut to a size of 10 cm diameter and 15 cm height. The completed sample was then placed on the top of the base plate of the resilient modulus testing machine. Three LVDTs were glued in the three sides of the sample's cured surface to measure the change in length due to change in temperature. The complete set was then placed into the environmental chamber. The preparation procedure of the cylindrical sample is presented in Figure 12.



(a) (b) (c)

(d) (e) (f)

Figure 12: Preparation of cylindrical asphalt sample (a) superpave gyratory compactor, (b) compacted sample, (c) coring of compacted sample, (d) cutting the edges of cored sample, (e) cylindrical sample, (f) sample in the UTM

Testing

Thermal-induced strains were measured by recording the readings of LVDTs for differential temperature changes. Temperature was controlled between 20°C and -17°C using a dynamic modulus environmental chamber. The temperature of the environmental chamber was changed by 2°C at a time interval of 1 to 1.5 hours for positive temperatures and 2 to 4 hours for negative temperatures. All measured strain data were zeroed against the associated value recorded for a temperature of 0°C. Figure 13 is the plot of thermal strain and temperature data during laboratory testing. From the figure, it is certain that thermal strain follows a similar trend with the temperature cycles.

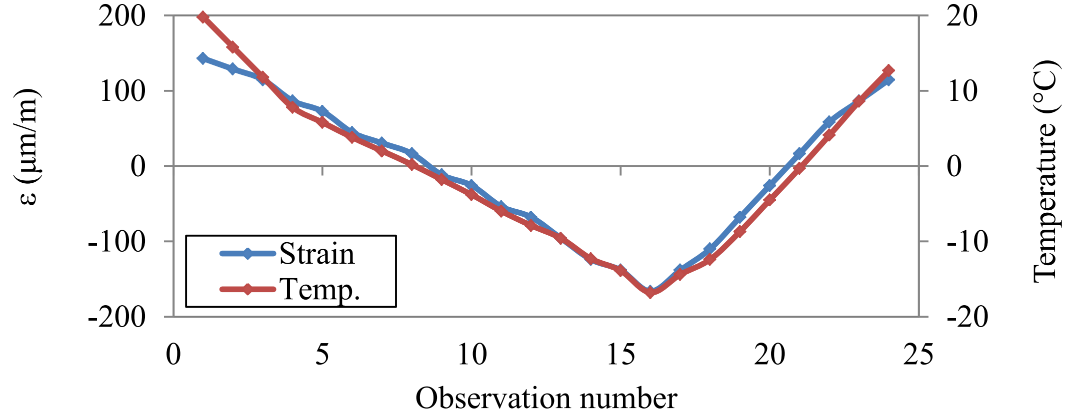


Figure 13: Variation of thermal strain of asphalt cylindrical sample with varying temperature

Heating and cooling phenomena for a temperature range of -17°C to 20°C are represented in Figure 14. An almost-similar trend is observed for heating and cooling. The heating curve coincides with the cooling line in most of the cases. Both heating and cooling lines are flatter at higher temperatures than at lower temperatures due to similar ΔT. This result indicated that strain generation is less at a higher temperature than at a lower temperature. CTC and CTE values were calculated from the cooling and heating lines respectively and the values were found to be 0.98 and 0.95, respectively, for a temperature range of 12°C to -17°C.

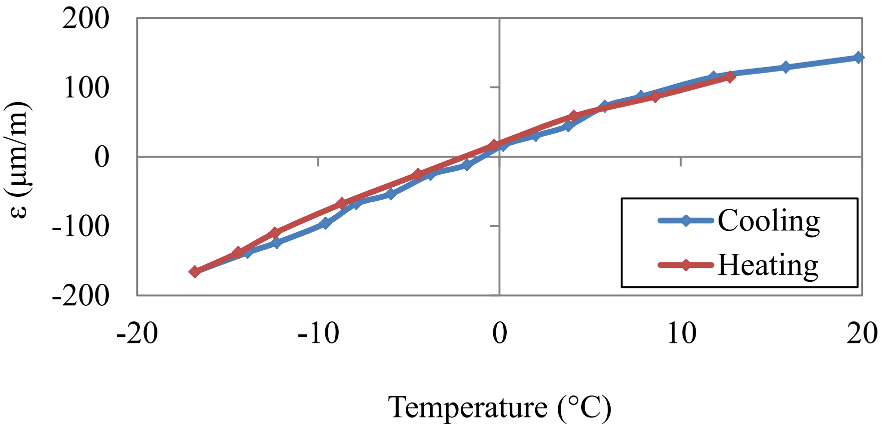


Figure 14: Variations of strain values upon cooling and heating

Table 4 shows the thermal-induced strain variation at higher and lower temperatures for similar ΔT. Thermal strain was measured for a temperature variation of 2°C to 9.8°C for different temperature ranges. It has been observed that thermal strain is 1.33 to 2.0 times greater in a lower temperature range than in a higher temperature range for a similar ΔT. This result is quite similar to the result of field observation.

Table 4: Variation of thermal-induced strain at higher and lower temperature ranges

Temperature range (°C)		ΔT	Strain	Temperature range (°C)		ΔT	Strain
Minimum	Maximum	(°C)	(μm/m)	Minimum	Maximum	(°C)	(μm/m)
5.8	7.8	2	14.05	-16.8	-14.4	2.4	28.11
7.8	11.8	4	28.11	-16.8	-12.3	4.5	42.16
5.8	11.8	6	42.16	-13.9	-7.9	6	70.27
3.8	11.8	8	70.27	-16.8	-8.7	8.1	98.38
2	11.8	9.8	84.33	-16.8	-6	10.8	112.44

Conclusion

This study discussed the results of field observation and laboratory tests to investigate the seasonal variation of thermal-induced strain in flexible pavement. Field observation data represents a similar trend of thermal strain, air and pavement temperature during a monitoring period of five months on the IRRF test road. Identical results were also obtained from the ten-day laboratory testing of an asphalt slab and short-term testing of an asphalt cylindrical sample.

According to field observation, daily strain generation has been found greater with a larger fluctuation of daily pavement temperature. Comparison of thermal strain generation in fall and winter indicated that strain generated in winter is 1.4 to 2 times greater than that generated in fall for similar daily variation of pavement temperature. The cooling and heating phenomena during the laboratory test of asphalt cylindrical sample shows that smaller strain is generated at a higher temperature range than at a lower temperature range due to similar ΔT. Thermal-induced strain has been found to be 1.33 to 2.0 times greater at a lower temperature range (-6°C to -16.8°C) than at a higher temperature range (2°C to 11.8°C). The cooling and heating phenomena during laboratory testing of asphalt slab confirms that smaller strain is generated at higher temperature ranges than at lower temperature ranges due to similar ΔT at the bottom of the HMA layer. Thermal contraction and expansion rates have also been found greater at lower temperature ranges.

The following conclusions can be made based on the study.

- Temperature and thermal strain follow similar trends according to field data and laboratory tests of an asphalt slab and cylindrical asphalt sample.
- Thermal-induced strain ratio has been found to be 1.33 to 2.0 according to field observation (ratio between strain measured at winter and fall) and laboratory test data (ratio between strain measured at lower and higher temperatures).
- A certain change in temperature causes smaller strain generation at a higher temperature range than at a lower temperature range according to laboratory test of an asphalt slab and cylindrical asphalt sample.